Georgia Institute of Technology

Cavity QED with atoms and ions

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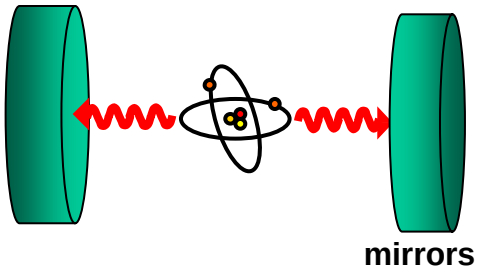
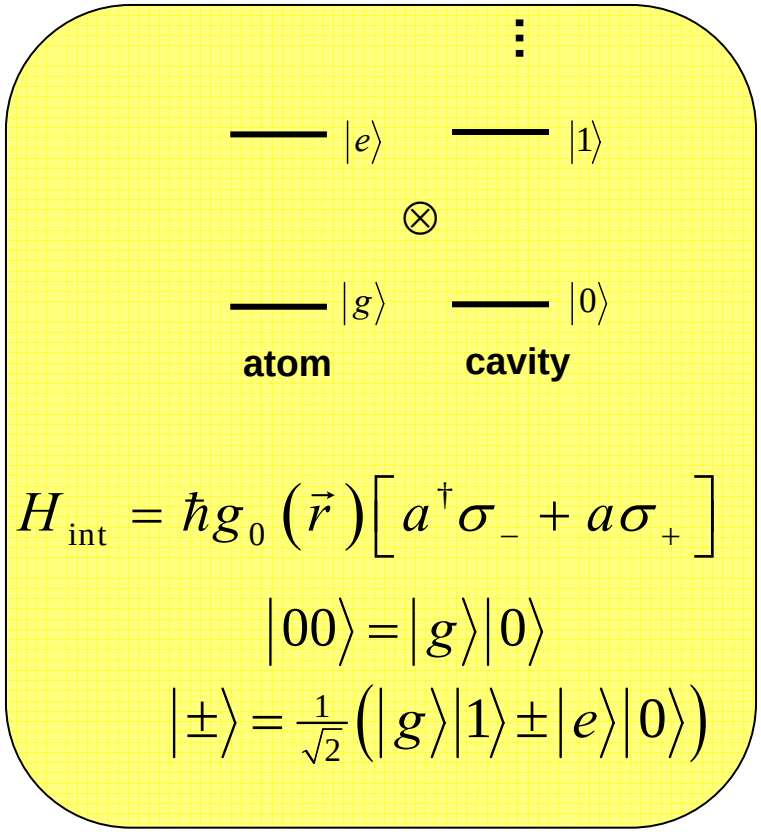
Cavity QED
1 atom + 1 photon

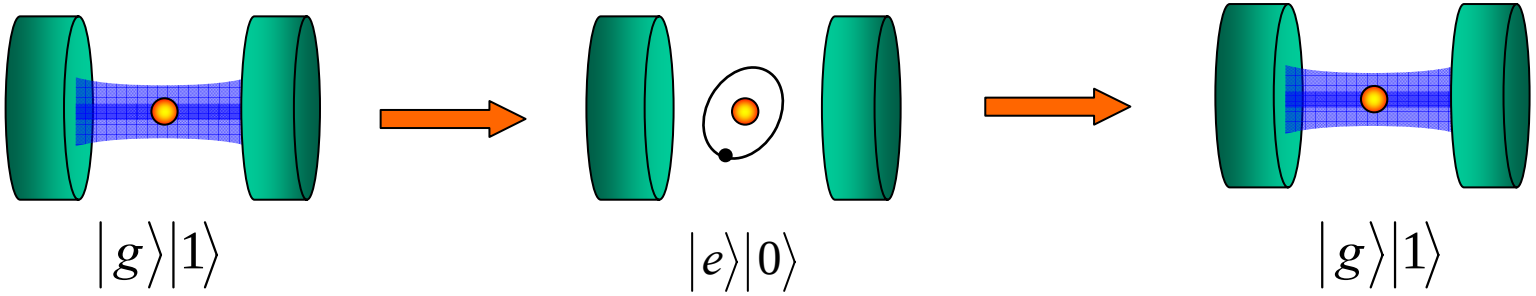




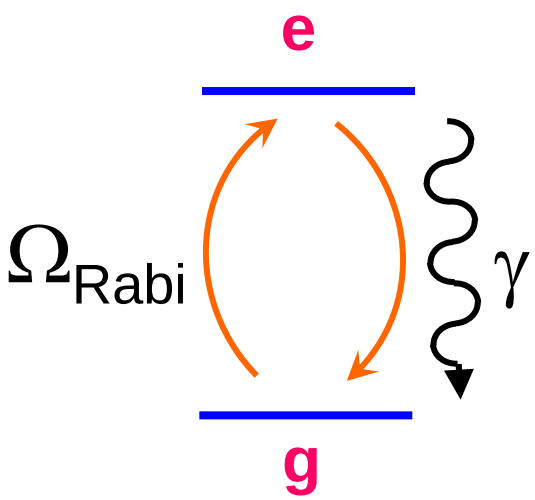
entanglements

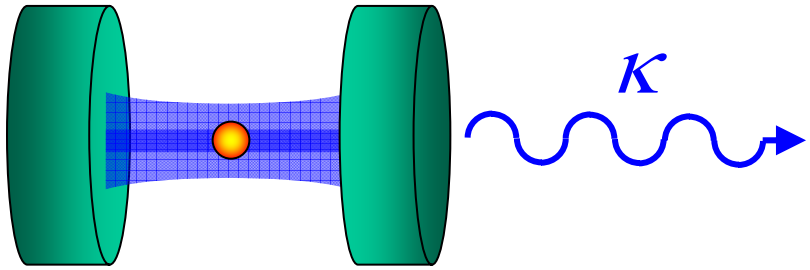
- atom-photon
- photon-photon
- atom-atom

Reversible, coherent 'spontaneous' emission (single photon Rabi flopping)



Cavity QED in the strong coupling regime— Rabi flopping with a single photon





Single photon Rabi frequency

$$g_0 \equiv \Omega_{Rabi}(1\text{ photon}) = \gamma\sqrt{I(1\text{ photon})/I_{sat}}$$

I (1 photon) — **intensity for 1 photon in cavity**

I_{sat} — **saturation intensity**

coherent Rabi flopping requires :

$g_0 > \gamma$ hence $I(1\text{ photon}) > I_{sat}$

$g_0 > \kappa$

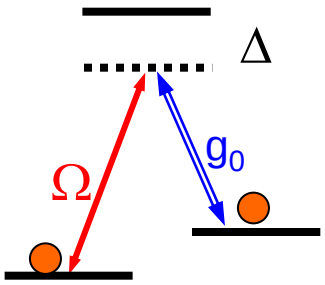
Cavity QED

Coherent coupling of matter qubits (e.g. single atoms) and photonic qubits

- **Entanglement generation**
  - **Atom-photon**
  - **Photon-photon**
  - **Atom-atom**
- **Quantum communication**
  - **Atoms are good material qubits**
  - **Photons travel well**
  - **CQED provides connection**
- **Cavities make good single atom detectors**

Estimating the success rate

Off-resonant Raman transition using cavity field



$$\Omega_{effective} = \frac{\Omega g_0}{2\Delta}$$ effective Rabi frequency

$$\Gamma_{effective} = \gamma\left(\frac{\Omega g_0}{4\Delta^2}\right)$$ effective spontaneous emission rate

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Coherence requires $\Omega_{effective} \gg \Gamma_{effective}$ and $\Omega_{effective} \gg \kappa$

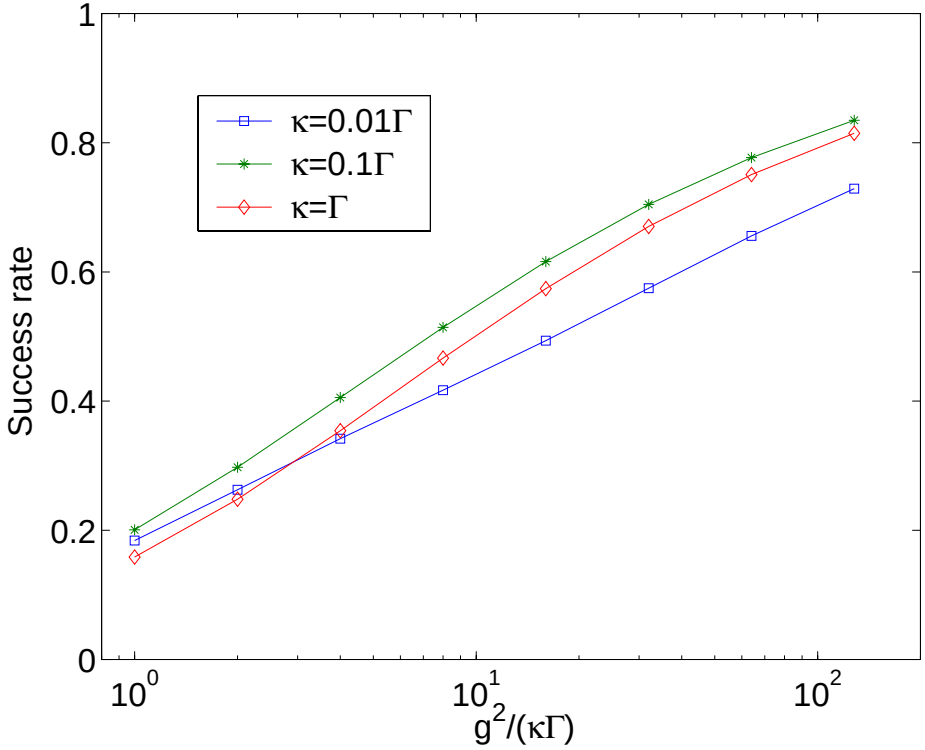
or $\frac{g_0^2}{\kappa\gamma} \gg 1$ and $g_0 \gg \kappa$

$\frac{g_0^2}{\kappa\gamma}$ is the atom cooperativity parameter

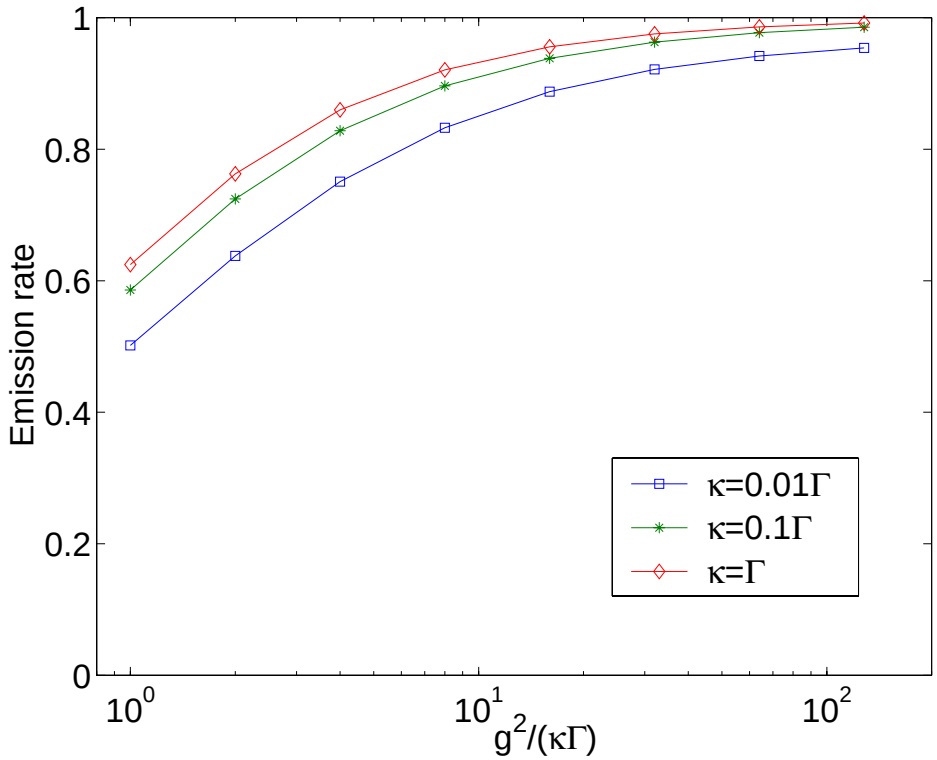
Success rate: $S_{optimal} = 1 - 2\frac{\sqrt{\kappa\gamma}}{g_0}$

Performance

State transfer (element of gate)



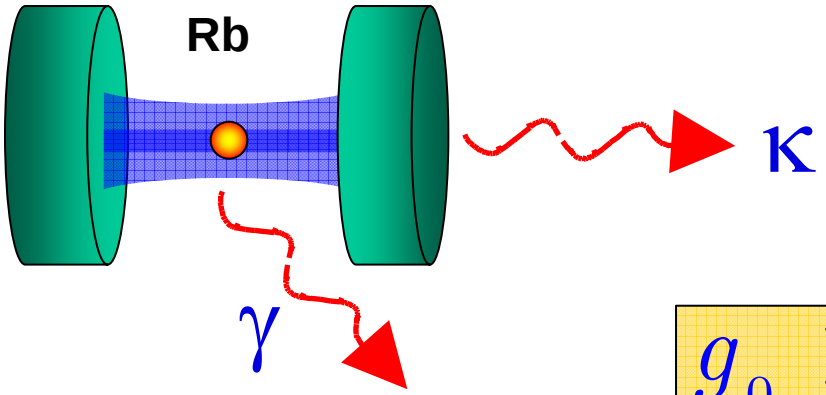
Single photon generator



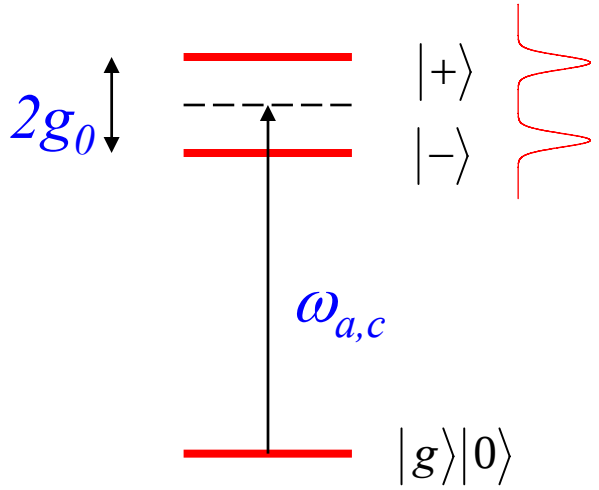
calculations by Li You

Conditional fidelities > 99% possible with cavity emission detection

Strong coupling



$$g_0 > \gamma, \kappa$$



$$g_0 = \vec{d} \cdot \vec{E}_0 \propto V^{-1/2}$$

$$g_0 = \sqrt{\frac{3c\lambda\gamma}{\pi\sqrt{2rL^3}}}$$

$$\kappa = \pi c / FL$$

$$F = 2\pi / \delta$$

$$C_1 = \frac{g_0^2}{\gamma\kappa} = 51$$

γ – atomic decay rate

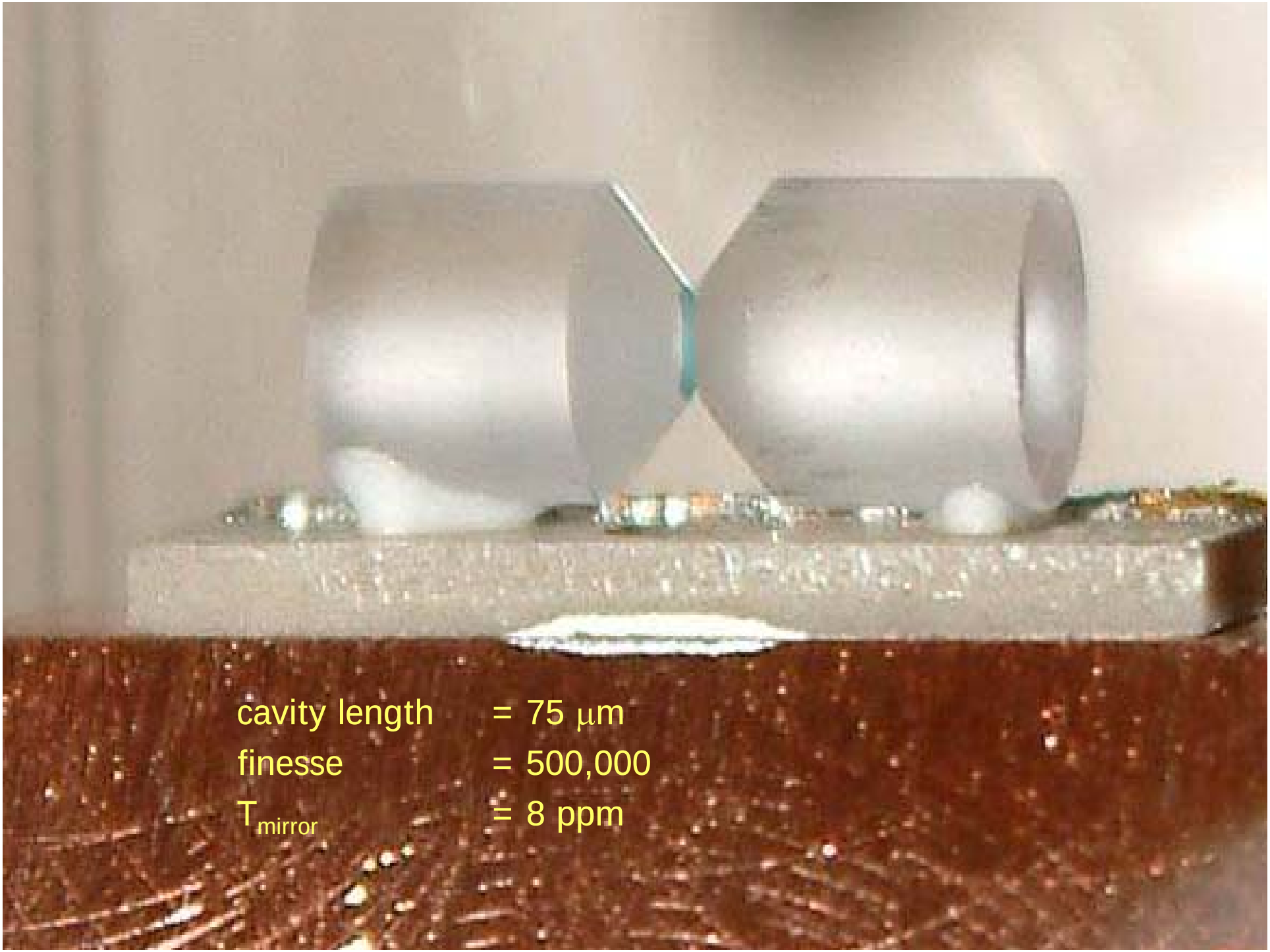
r – mirror radius of curvature

L – cavity length

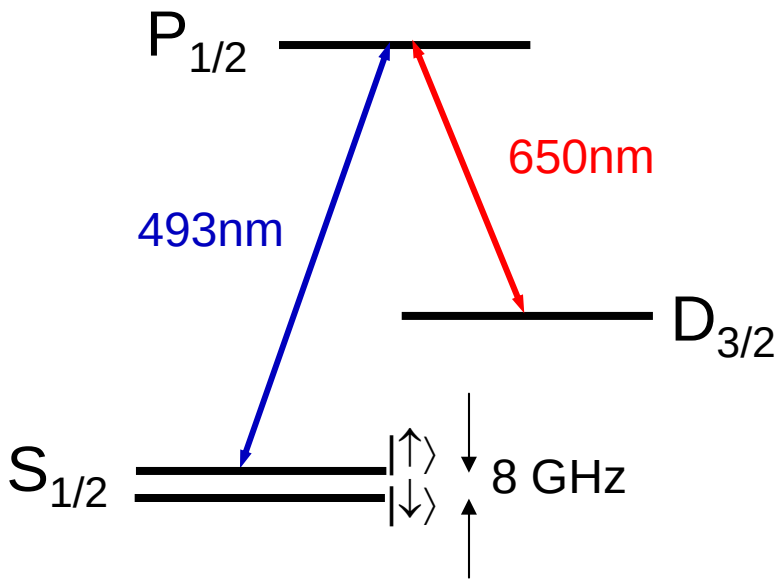
L < 1000 μm for strong transitions

Finesse, F > 100,000 required for $g > \kappa$

r > 1 cm for super-polishing


cavity length = 75 μm
finesse = 500,000
T_{mirror} = 8 ppm

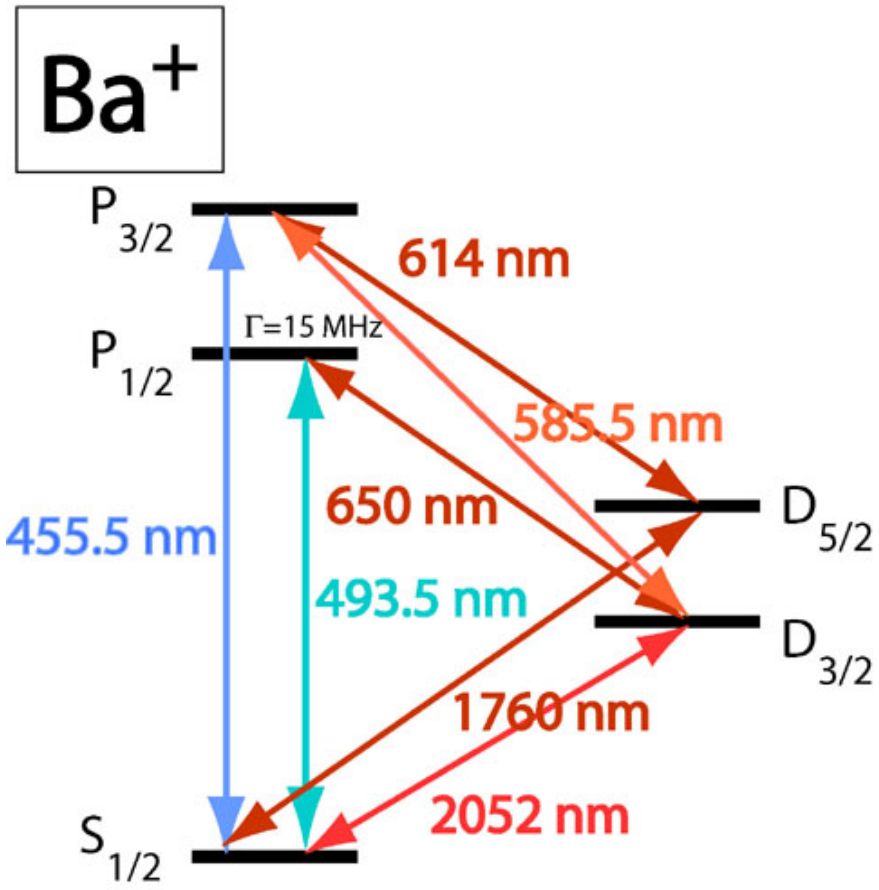
Trapped Ba^+ Ion Cavity QED

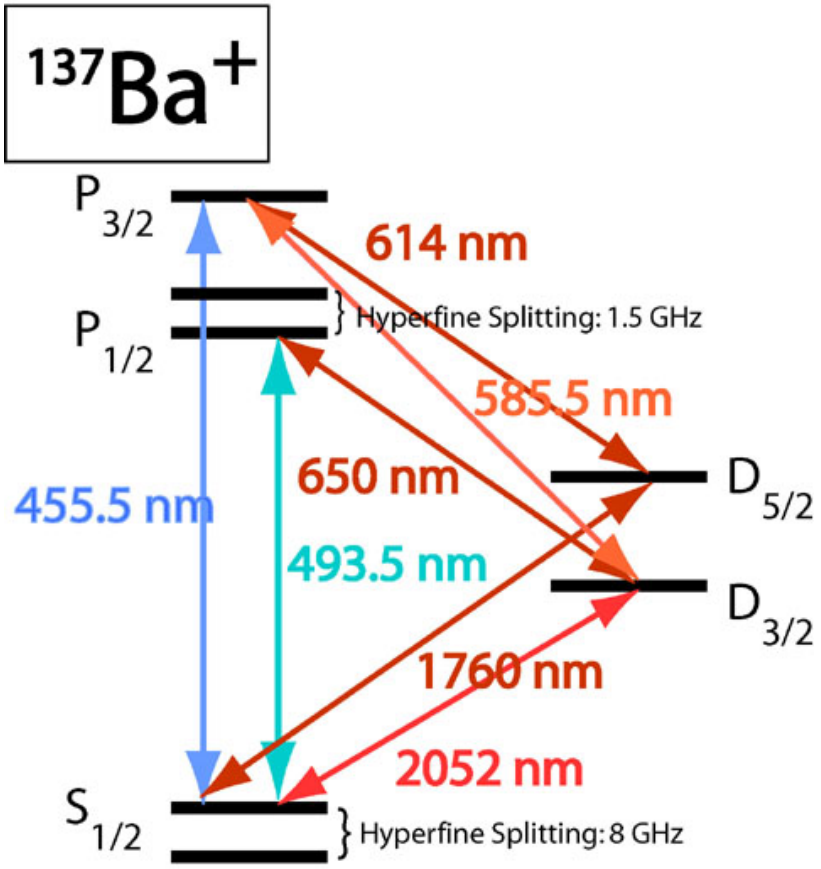


Ba^+ advantages:

- Convenient lasers
- High finesse cavities possible on both blue and red transition
- Strong coupling regime possible with ~1 mm cavities

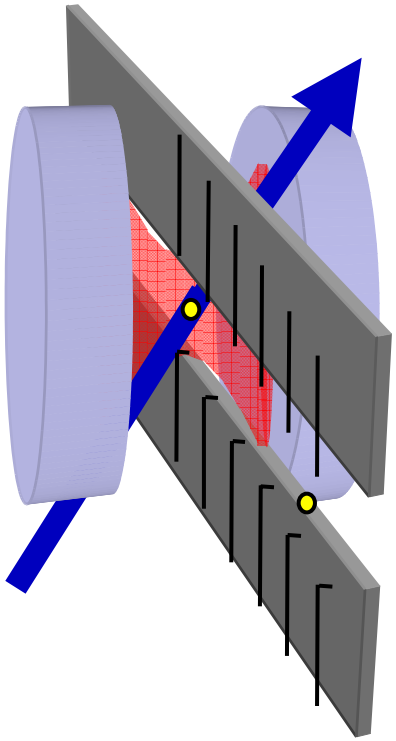
Relevent Ba+ levels

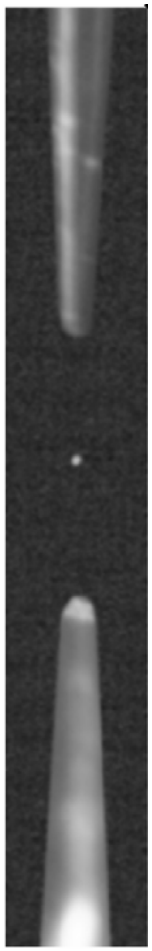




“borrowed” from Michigan ion trap database

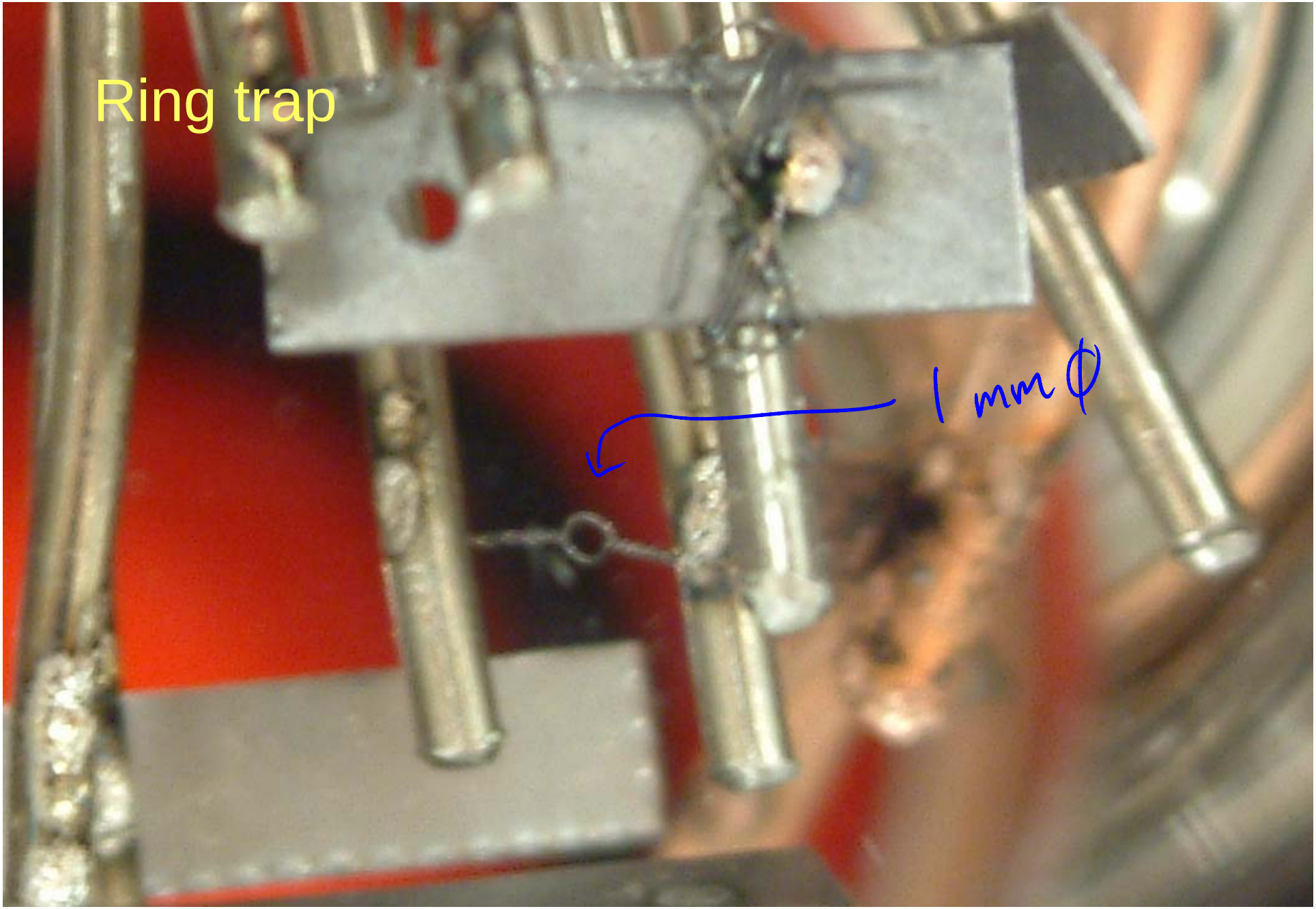
Integration challenges

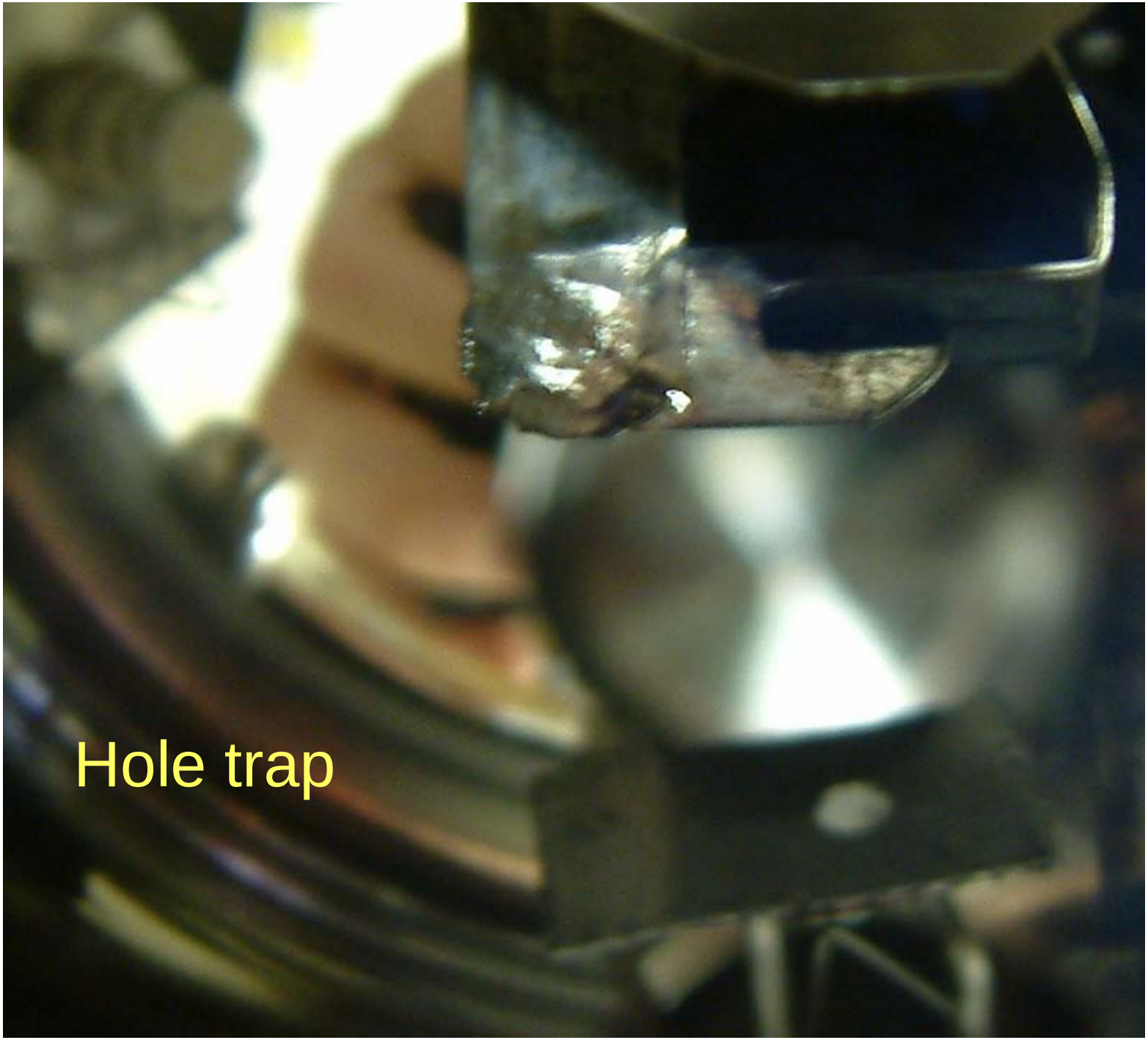


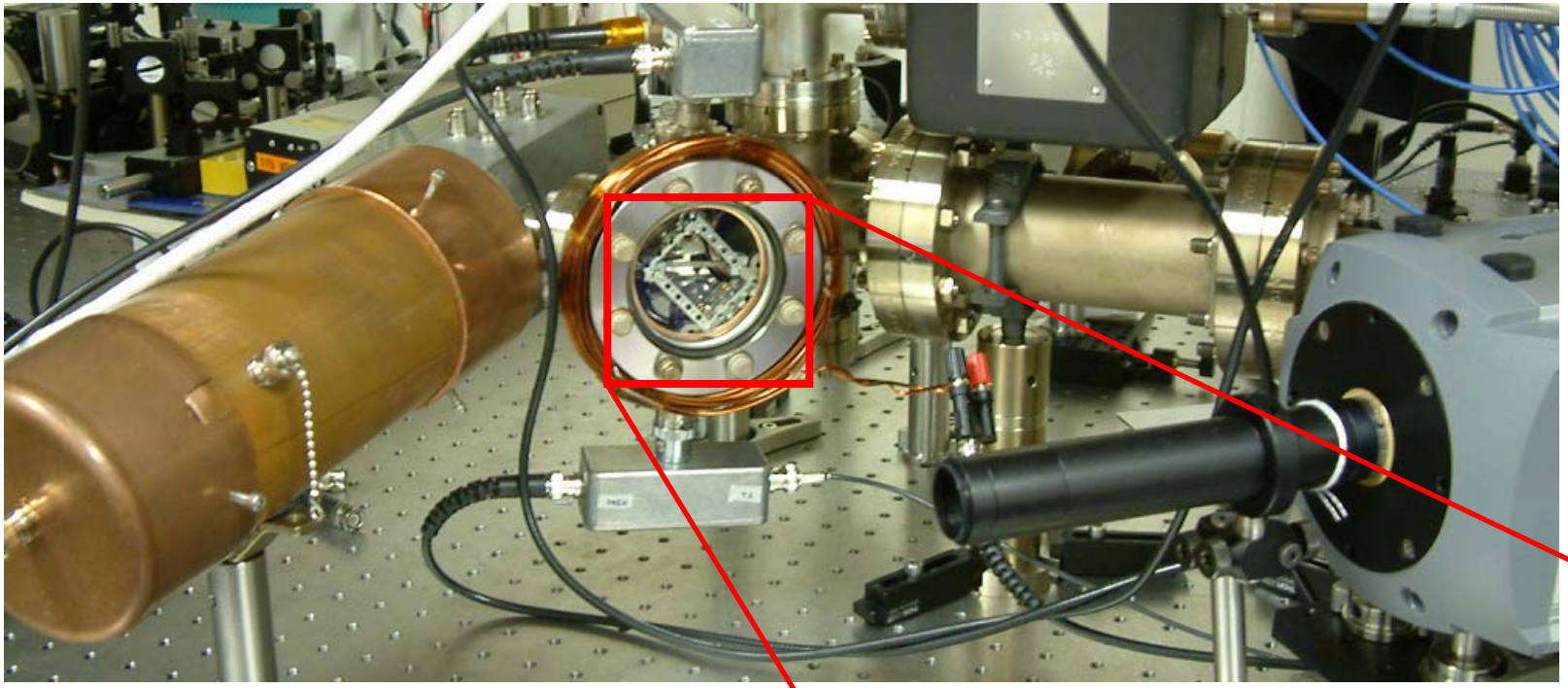


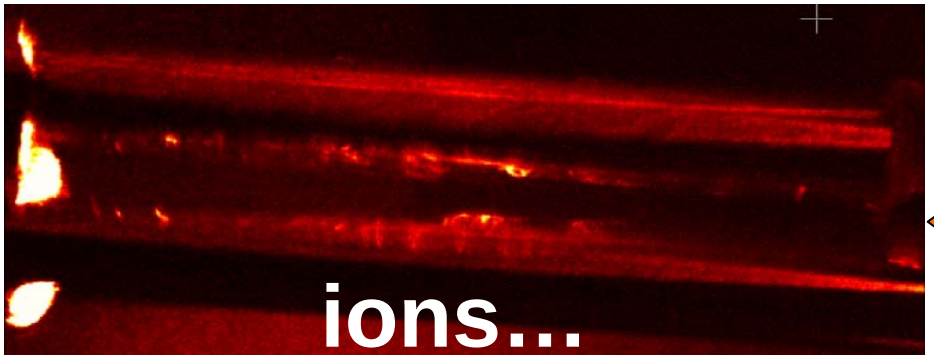
- Integrating small cavities with ion trap electrodes
- Minimizing charging of mirrors and effects of mirror dielectrics

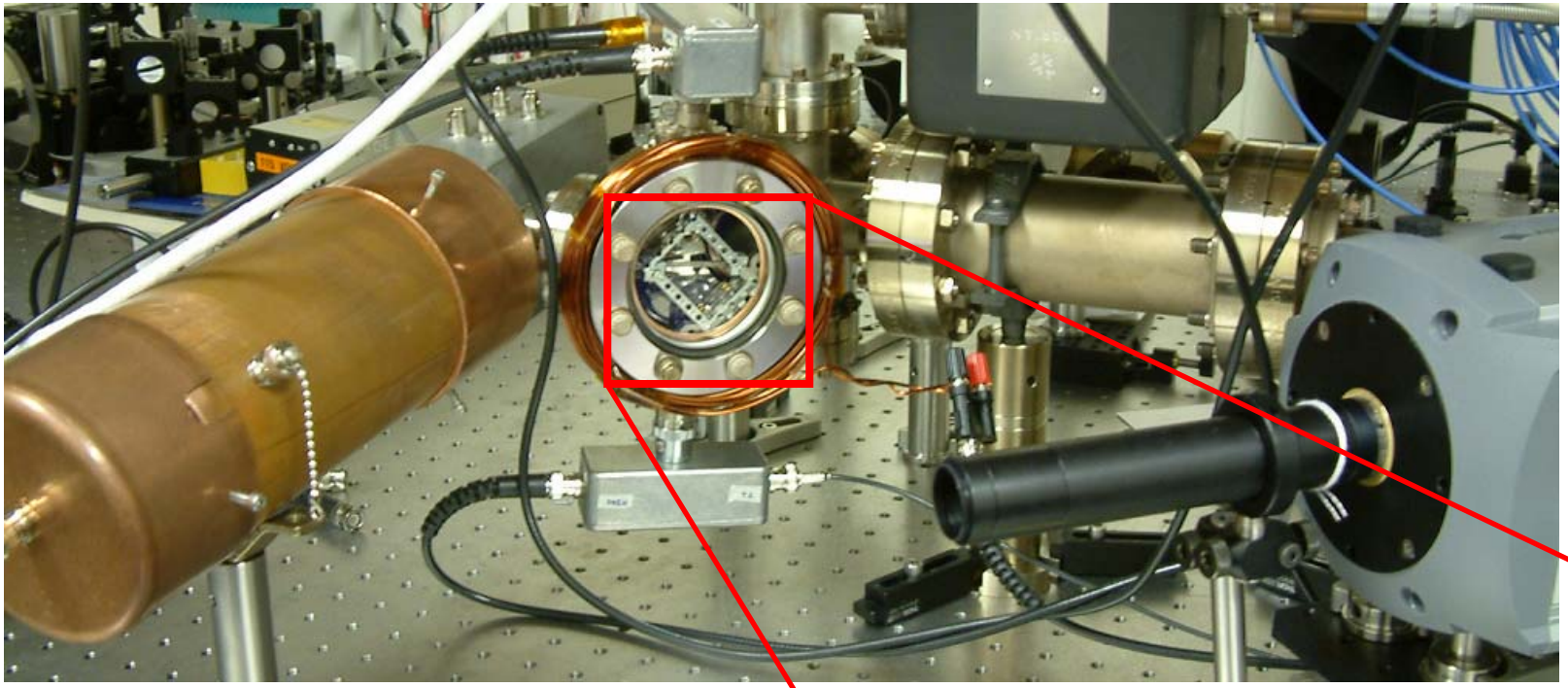
Possible micro-traps (Michigan)

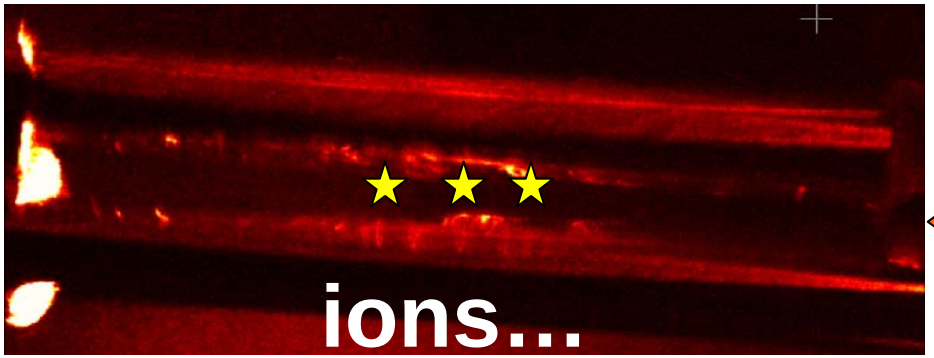

Ring trap
1 mm ϕ


Hole trap




ions…

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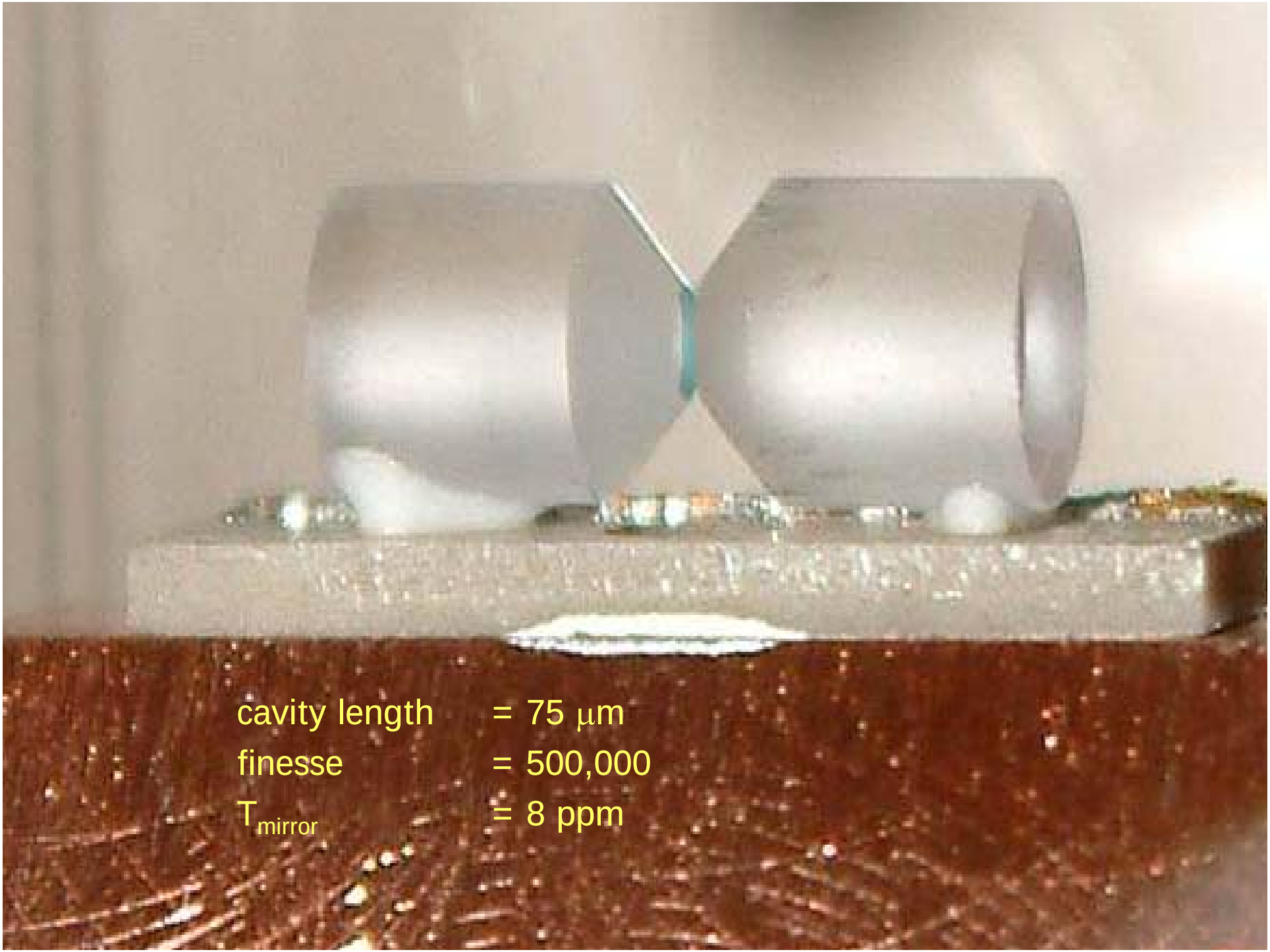
cavity length = 75 μm
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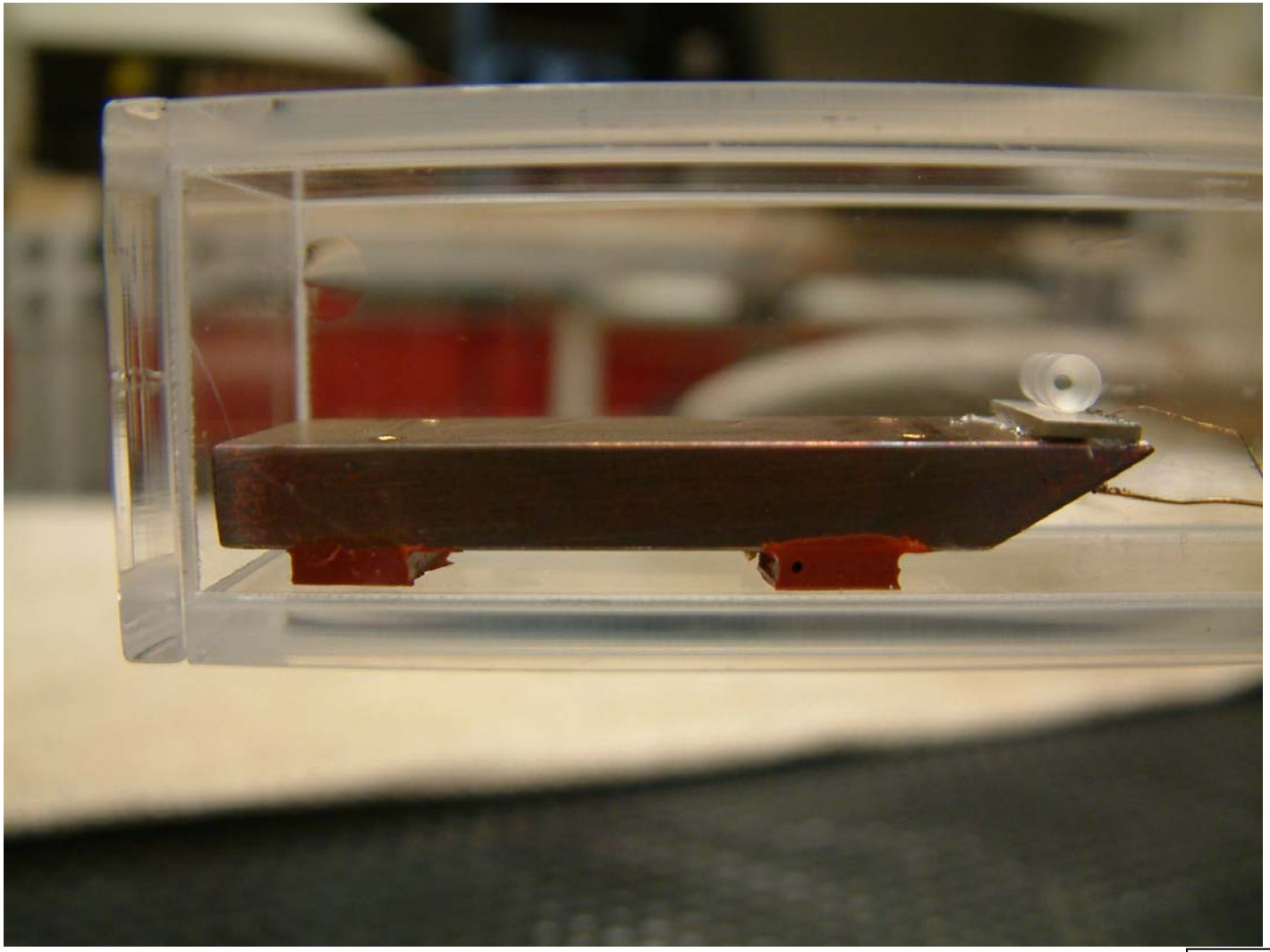


CAVITY 3

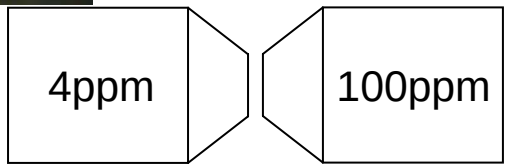
$l = 221.5\ \mu m$

$R = 2.5 cm$

$\frac{\kappa}{2\pi} = 5.73\ MHz$

$\frac{g_0}{2\pi} = 17.7\ MHz$

$\Im = 58{,}000$



1-sided Cavity

strong coupling regime

$$g_0 > (\kappa, \gamma)$$

How to get an atom in the cavity

Atomic beams

Falling cold atoms

- single atom transits observed

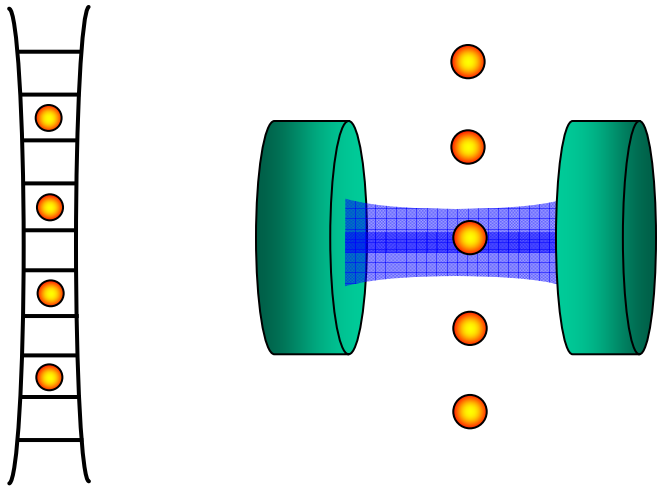
Catching the falling atoms

- trapping using the cavity modes

Caltech
MPQ (Rempe)

Trapping the atoms externally and transferring them into the cavity

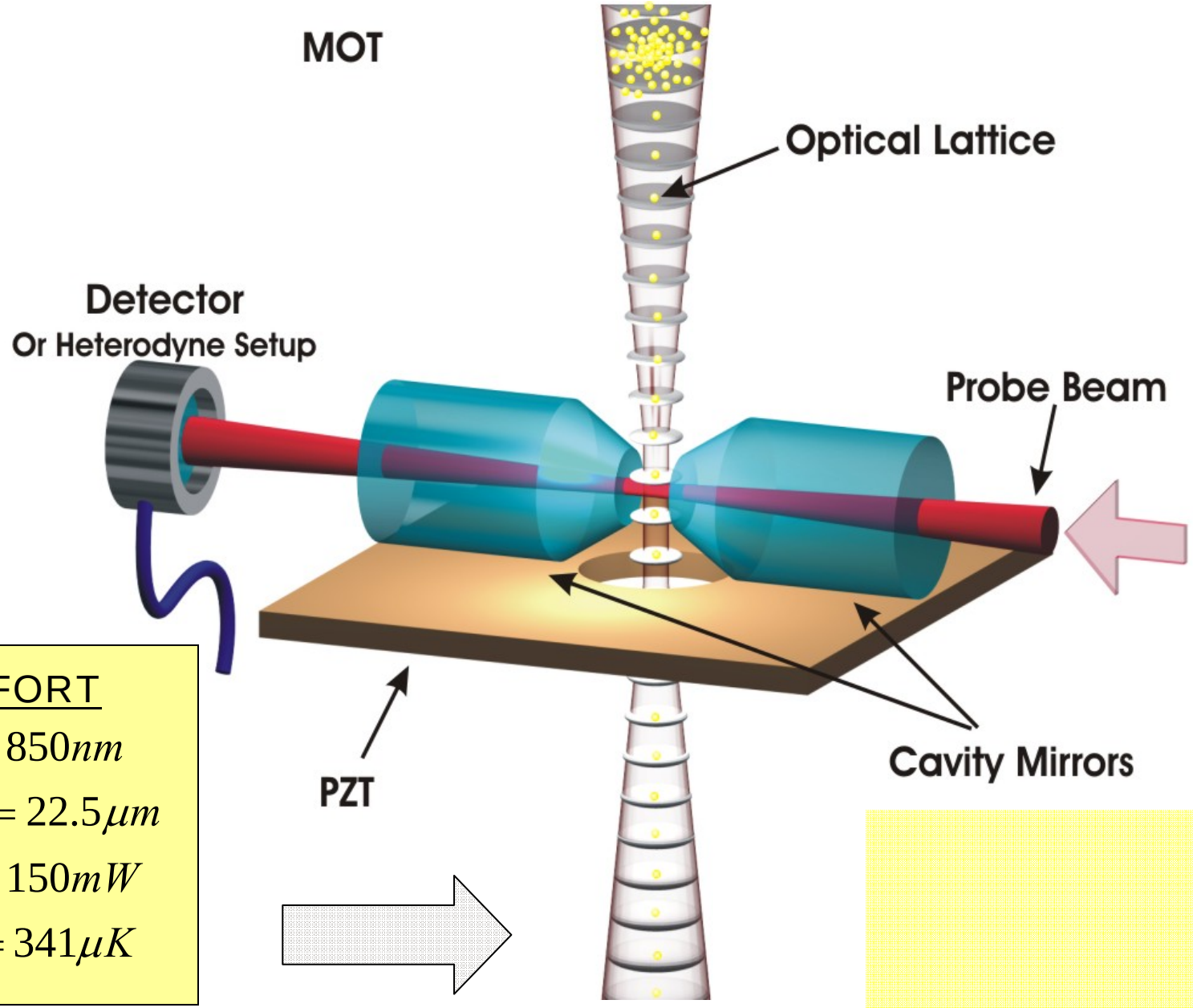
Georgia Ttech
MPQ (Rempe)



also, single trapped ions

MPQ (Lange), Innsbruck

Our System



FORT

$\lambda = 850nm$

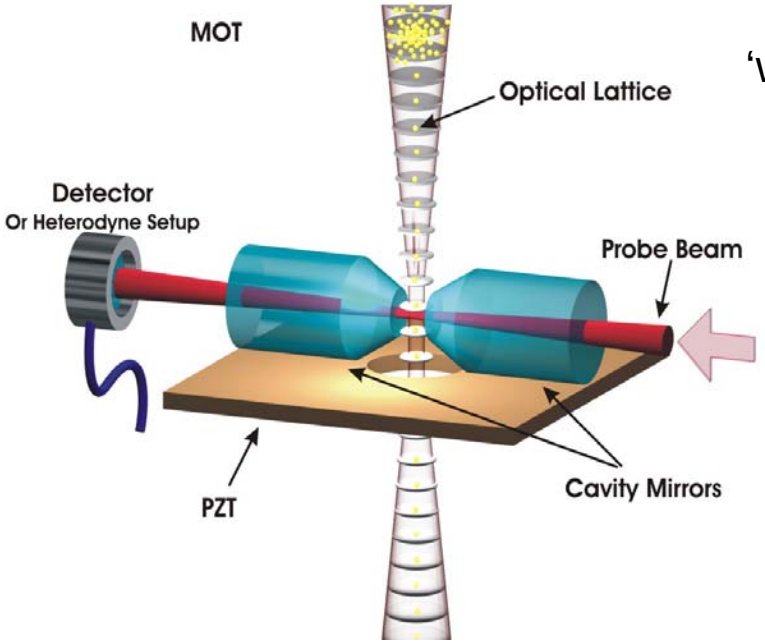
$w_0 = 22.5\mu m$

$P = 150mW$

$U = 341\mu K$

Neutral atom ^{87}Rb work

Optical Lattice

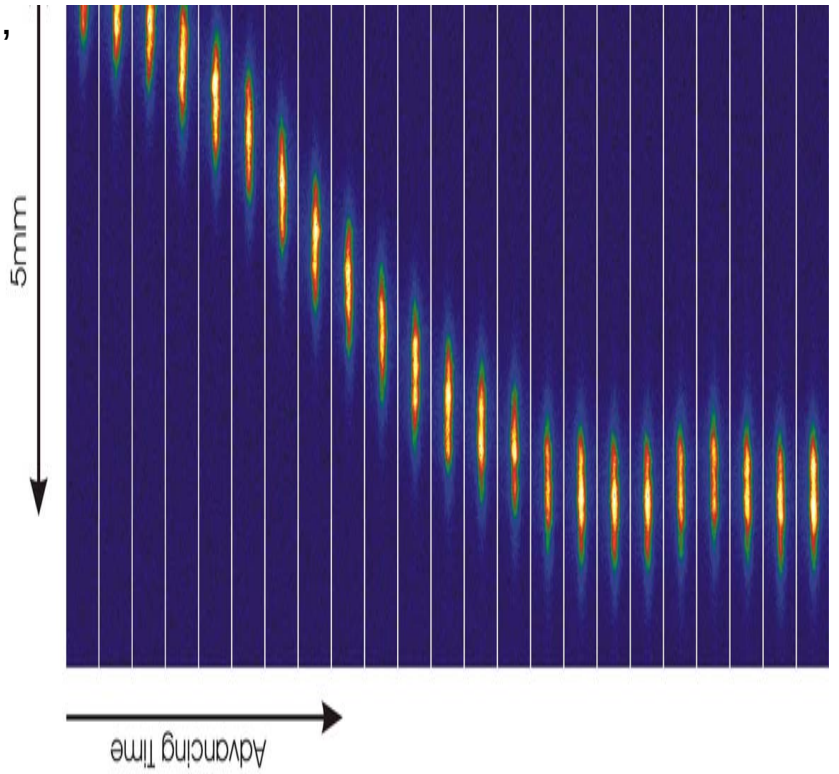


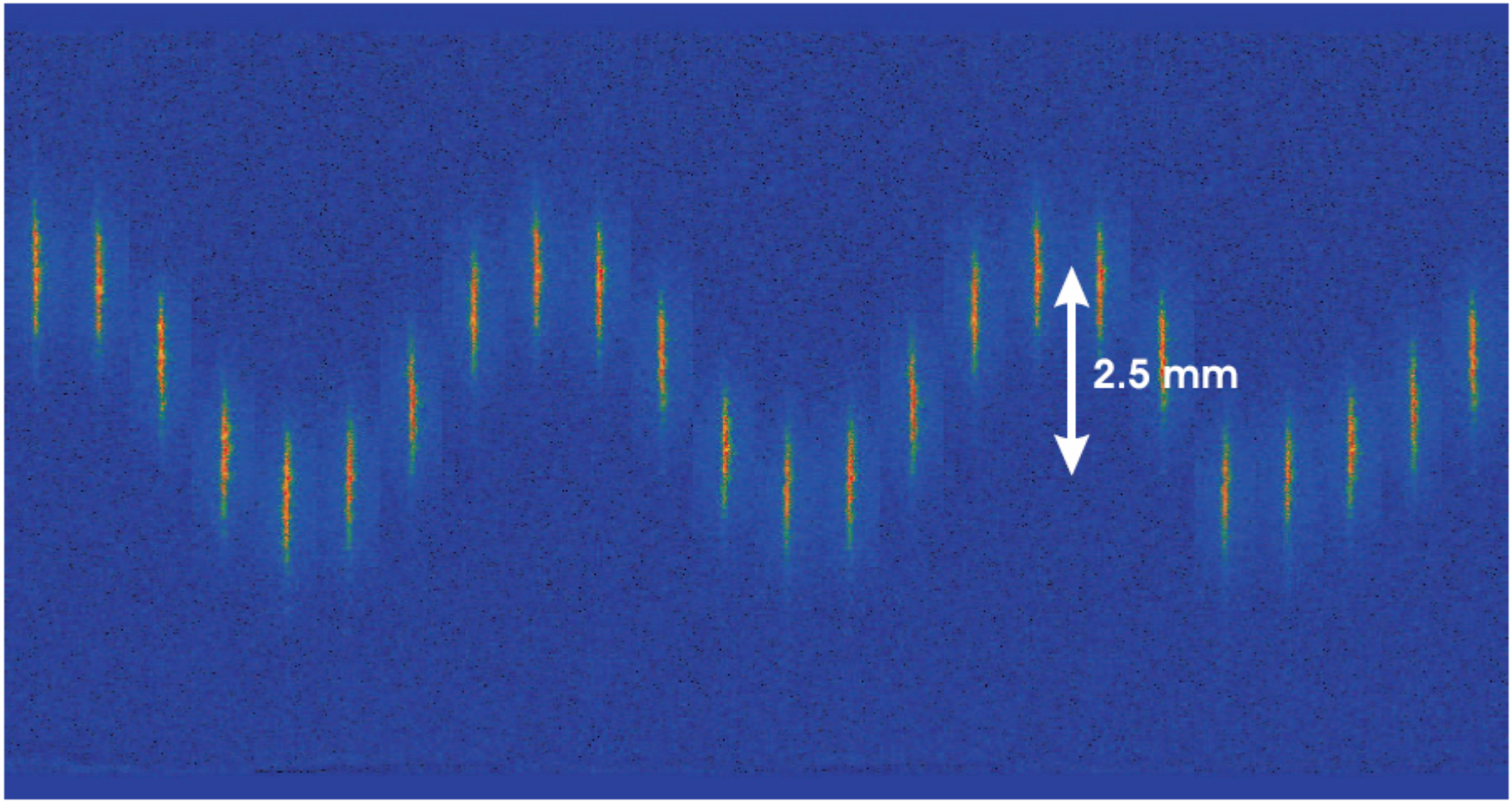
‘walking wave’

ν_1

ν_2

$v = \lambda \, \Delta\nu / 2$

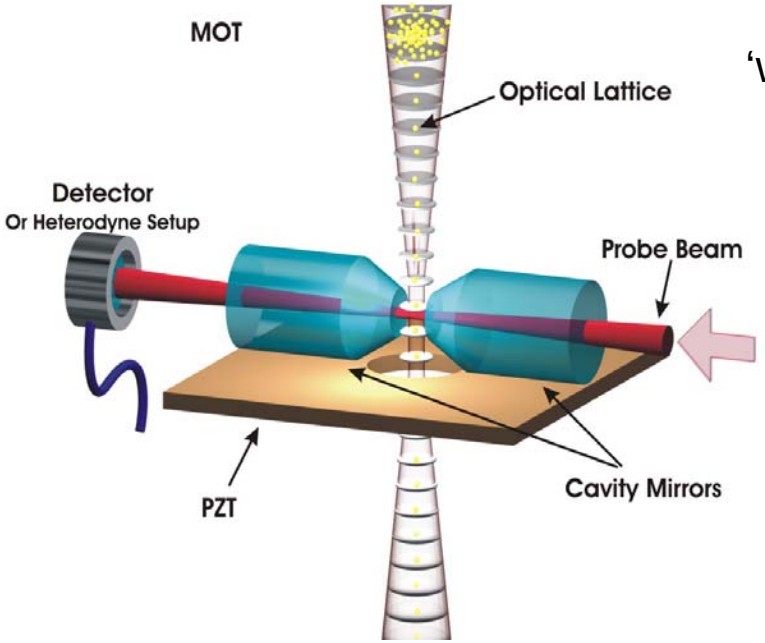




1 ms/frame

Neutral atom ^{87}Rb work

Optical Lattice



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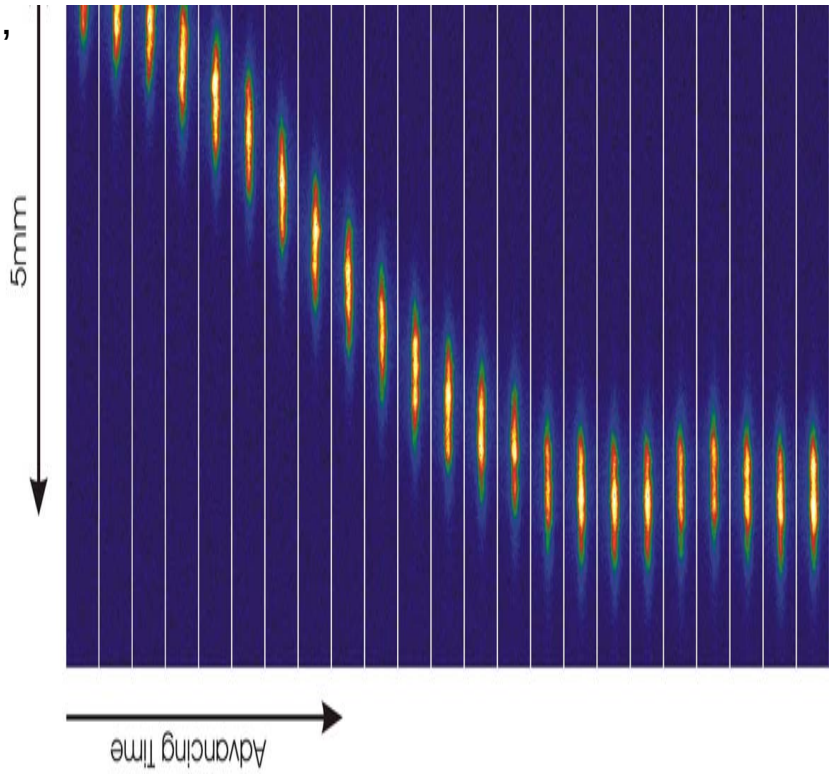
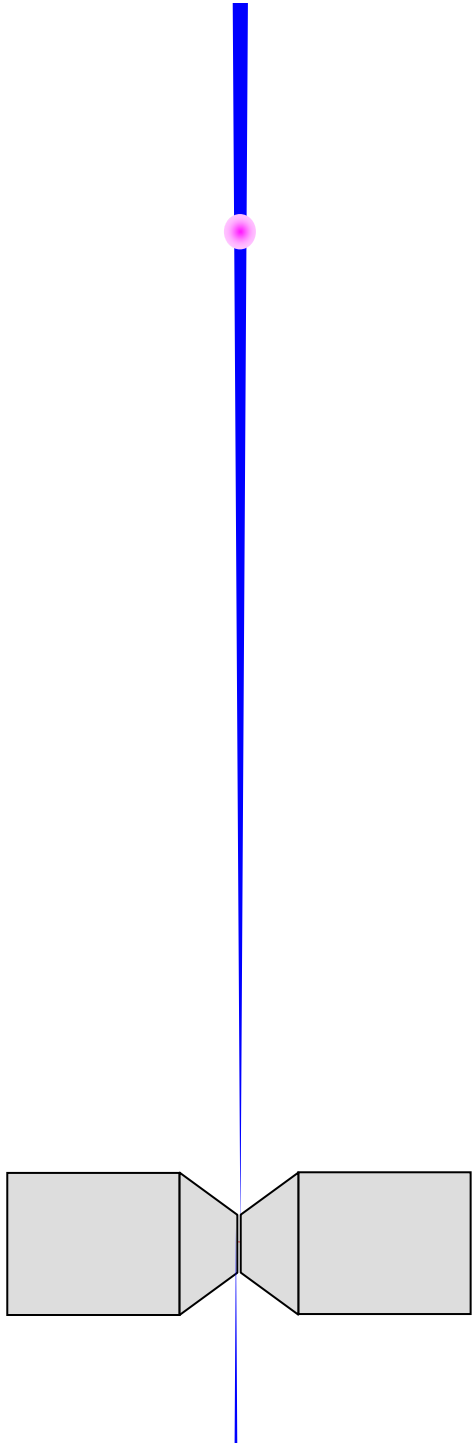
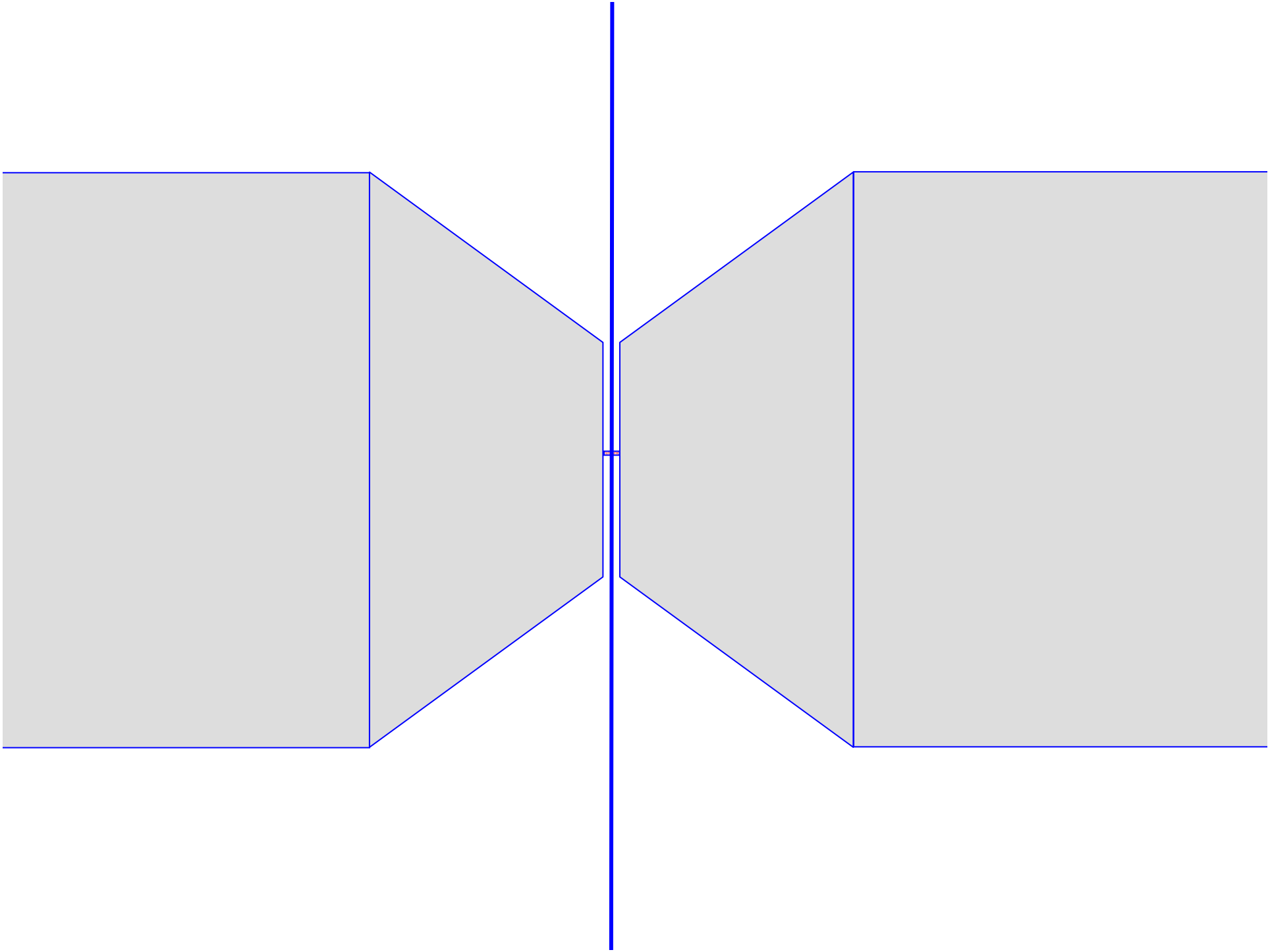
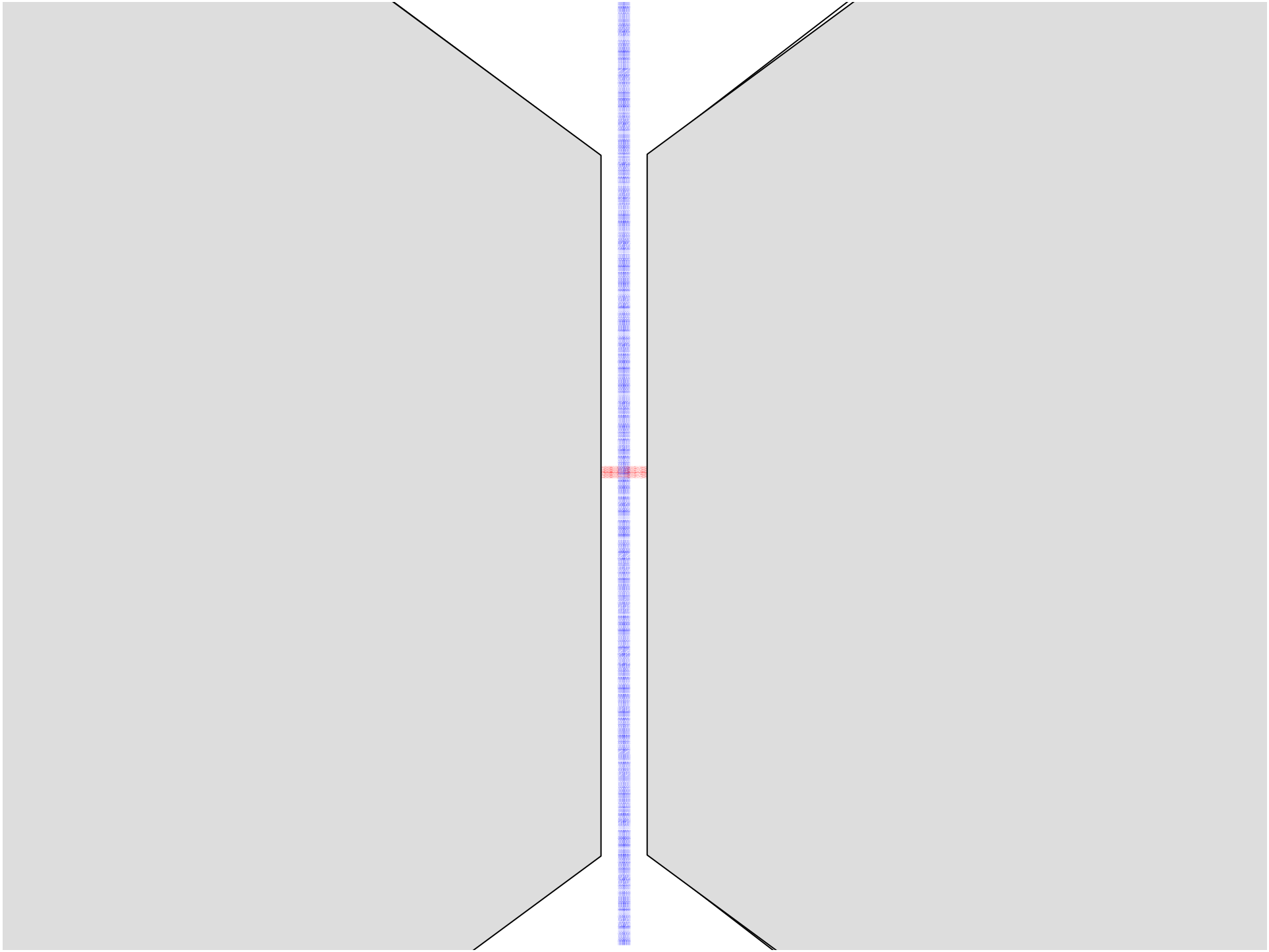
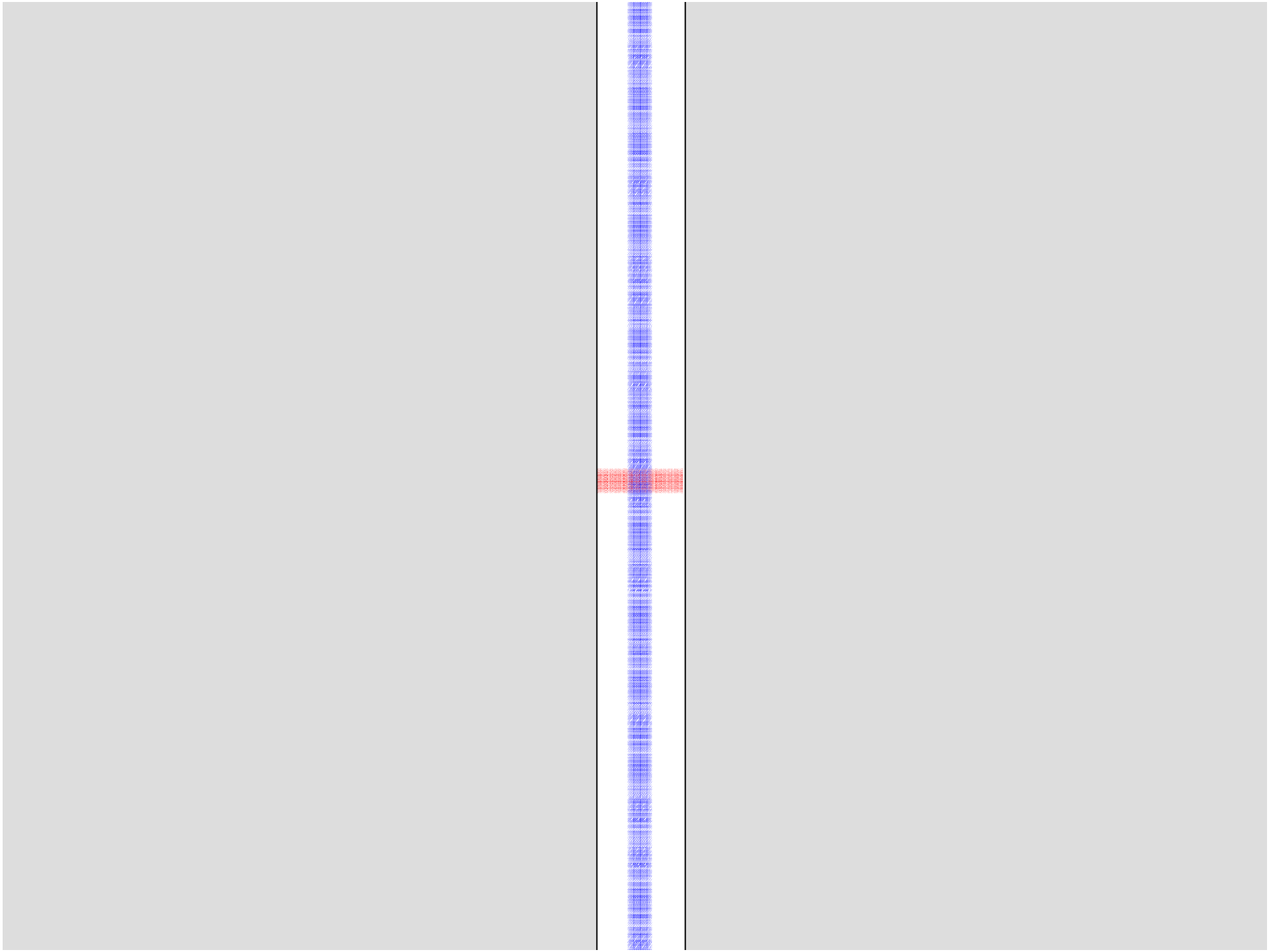
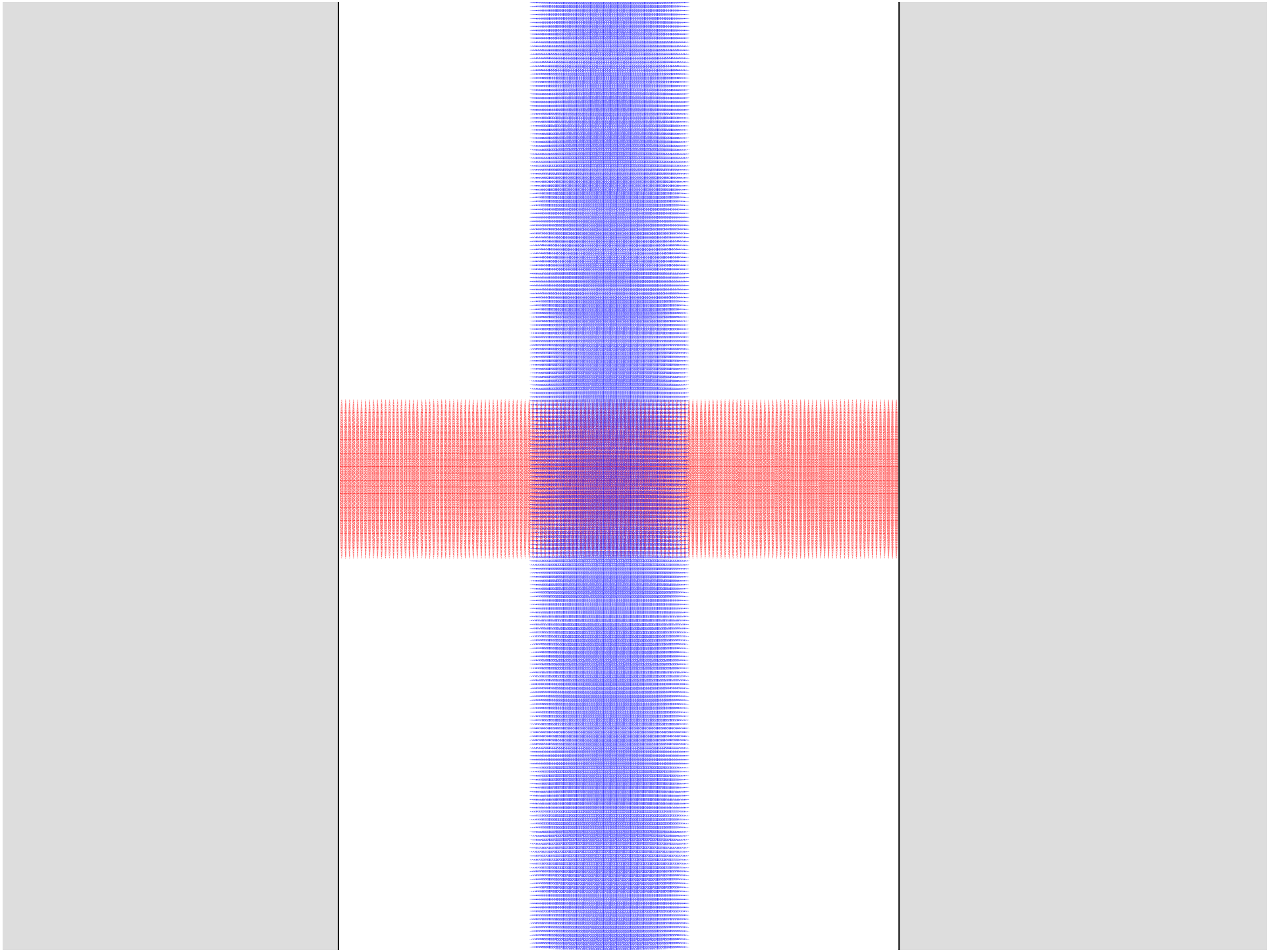


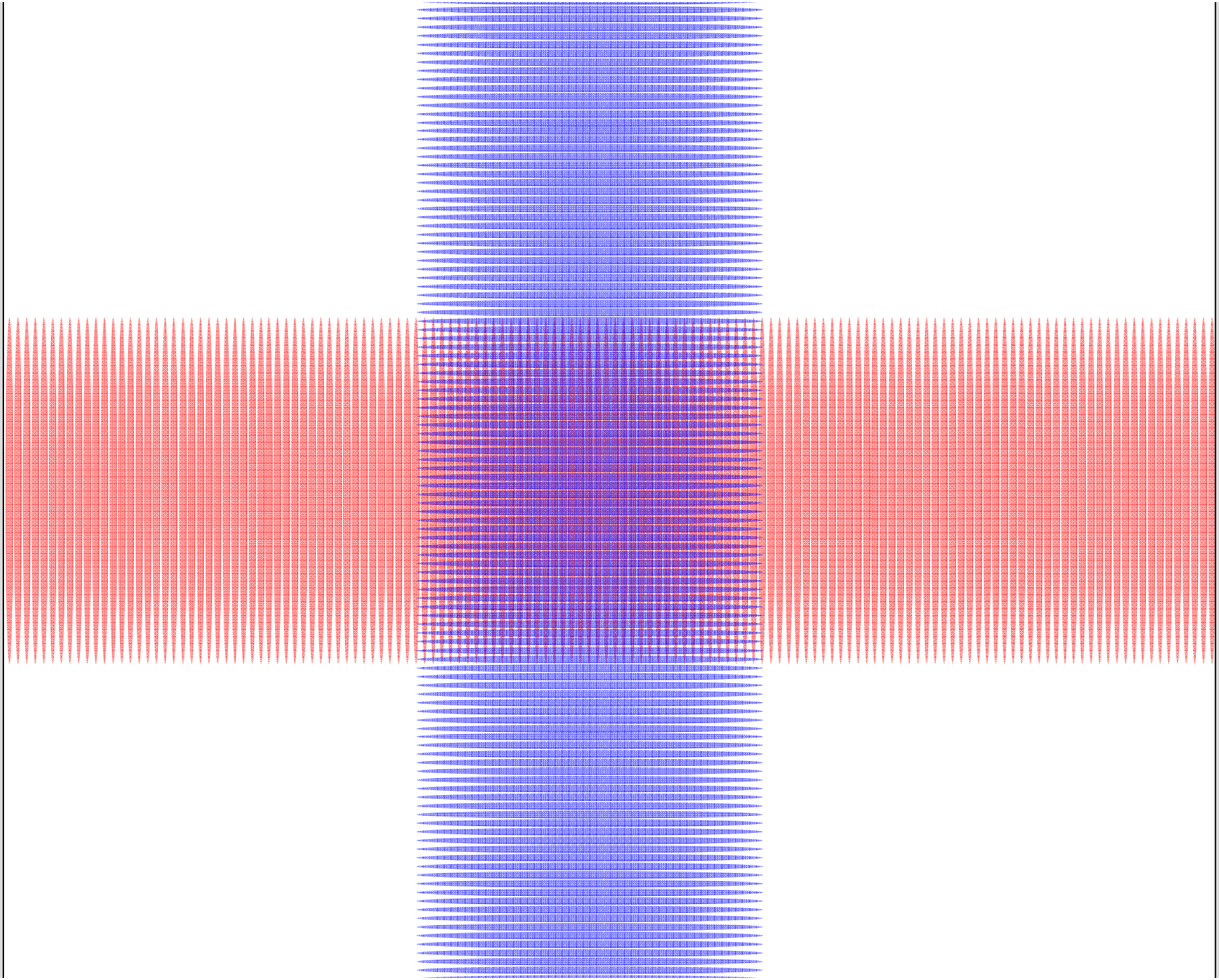




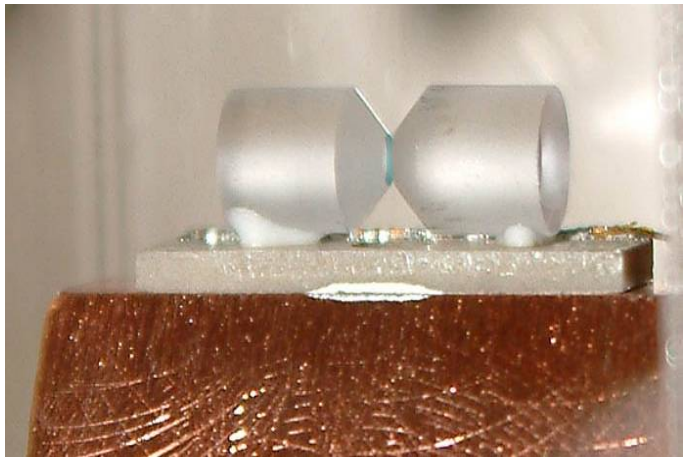




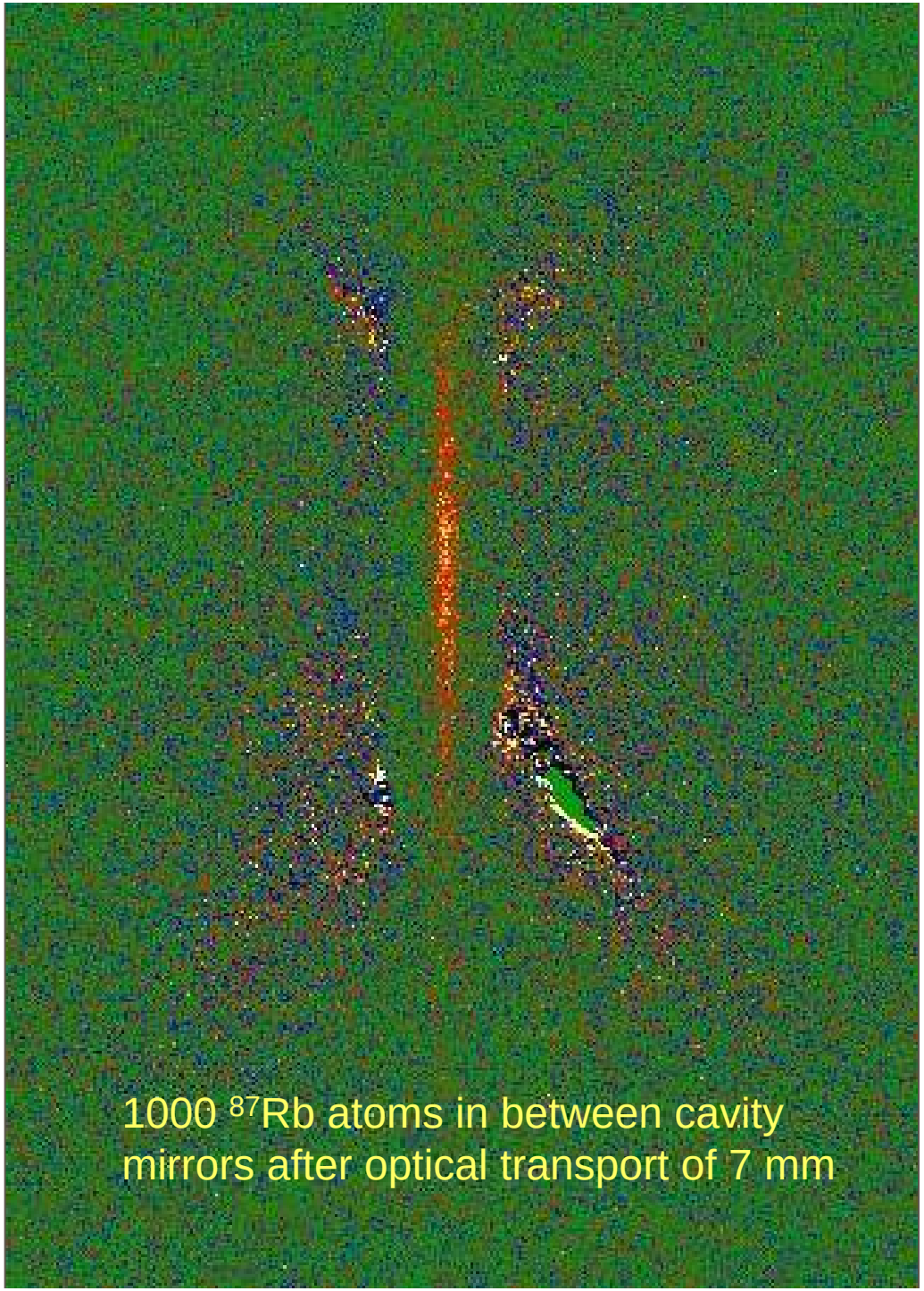




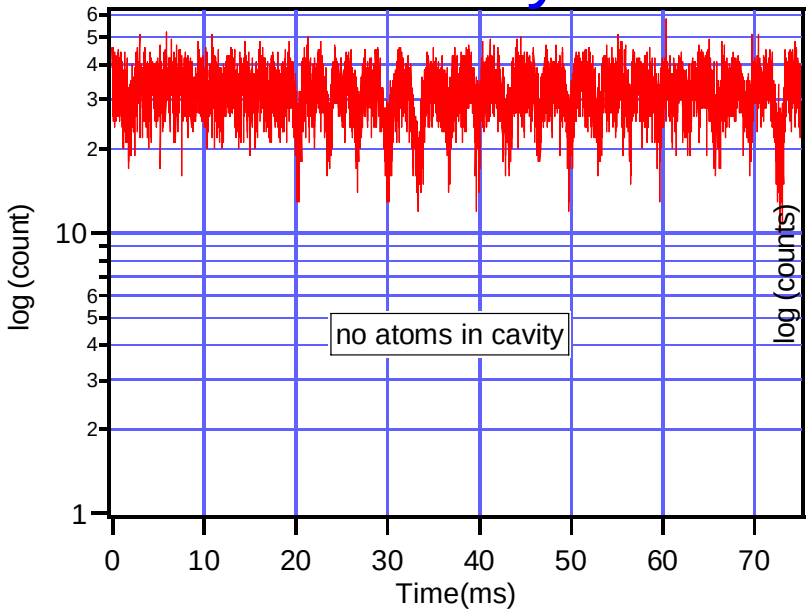
Improved Imaging allows us to image atoms in the cavity

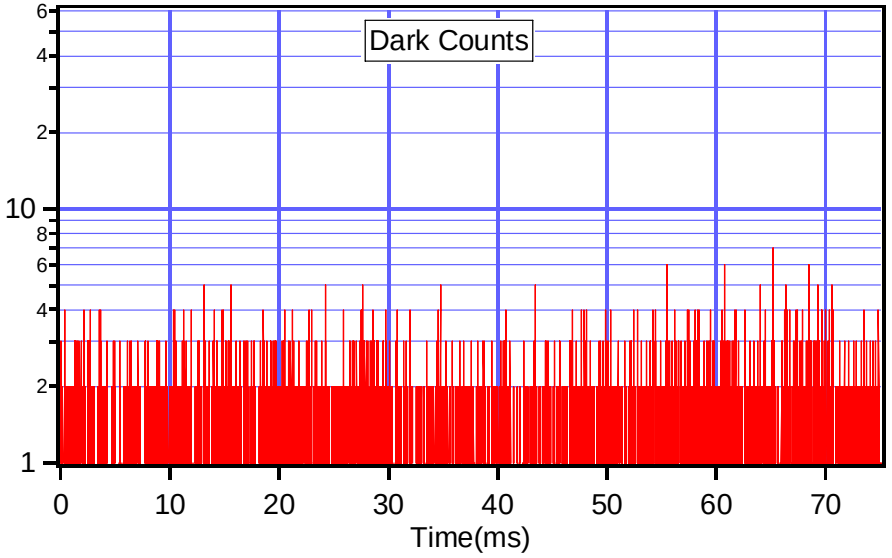


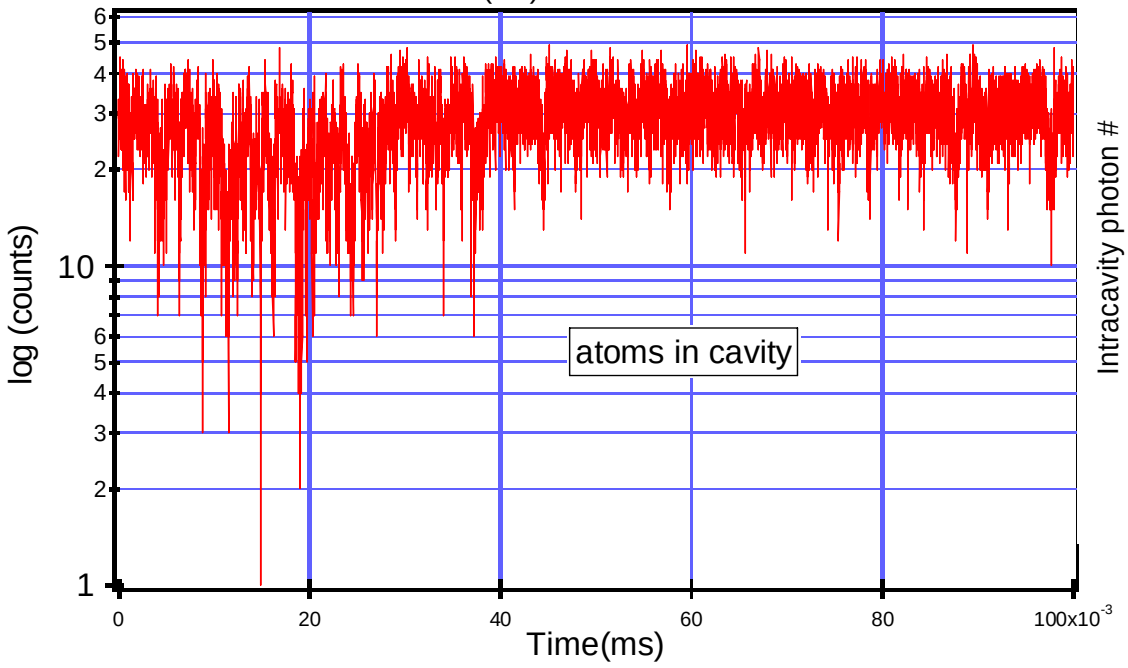
Mirror Separation $= 225\,\mu\mathrm{m}$

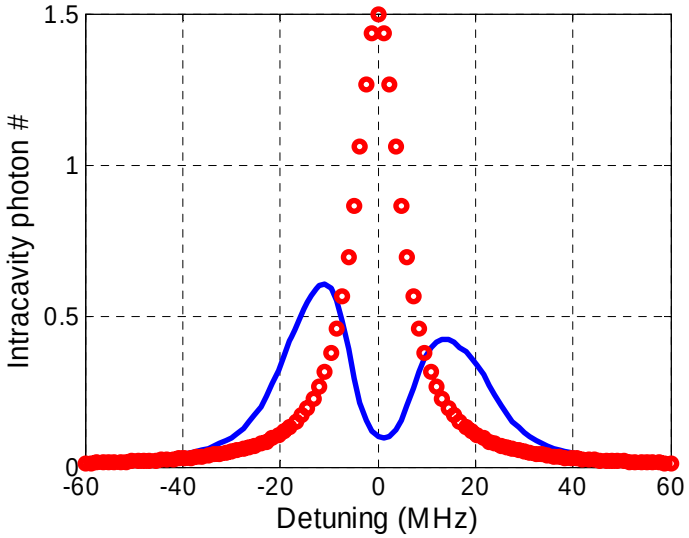


Cavity detection of atoms



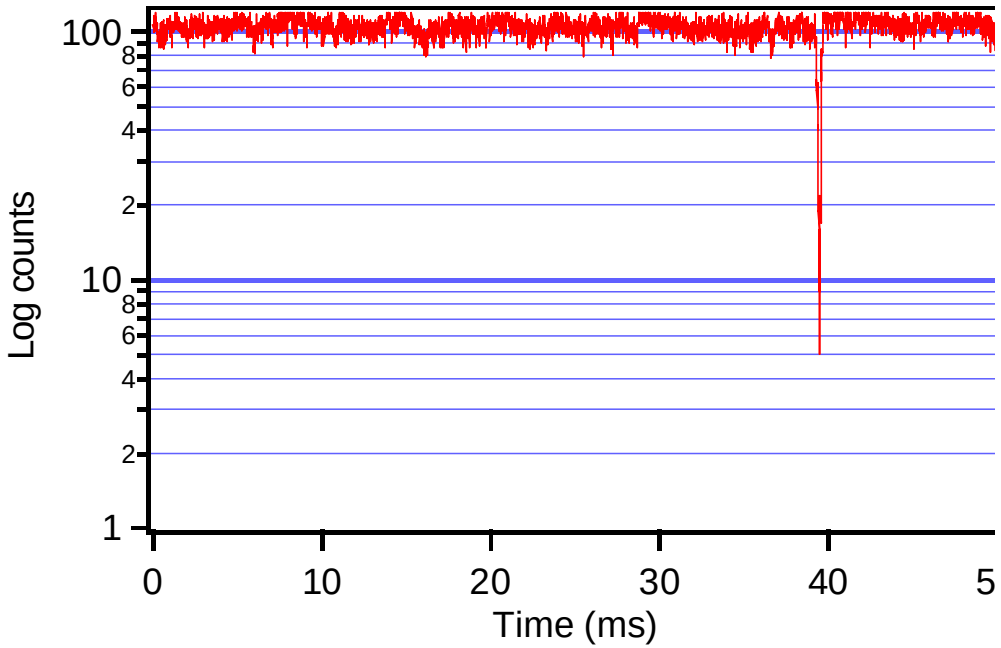




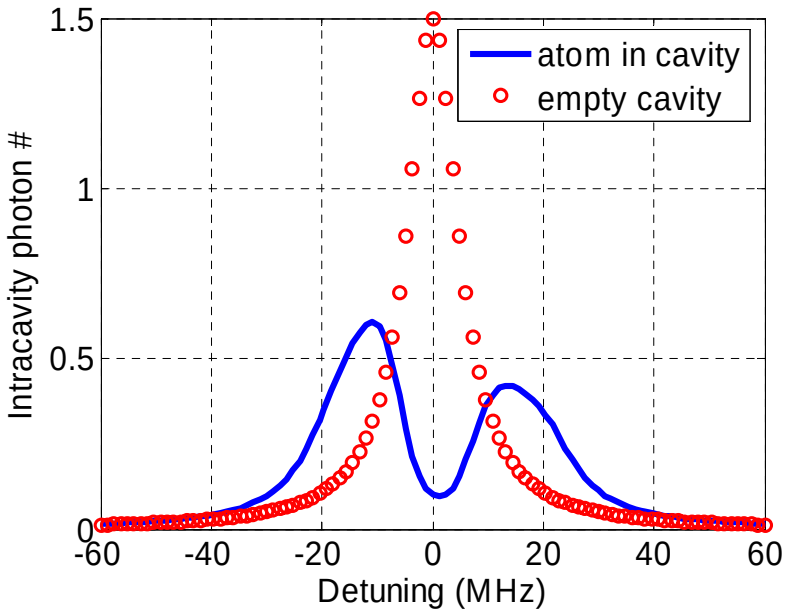


Theoretical plot
n=1.5

Single atoms in cavity



Atoms entering cavity, n=1.1 photons



Theoretical plot for n=1.1

Improving the single atom signals

"distill" from many atoms to a single atom in cavity

- Intercavity cooling for "non-destructive" intercavity detection of atoms

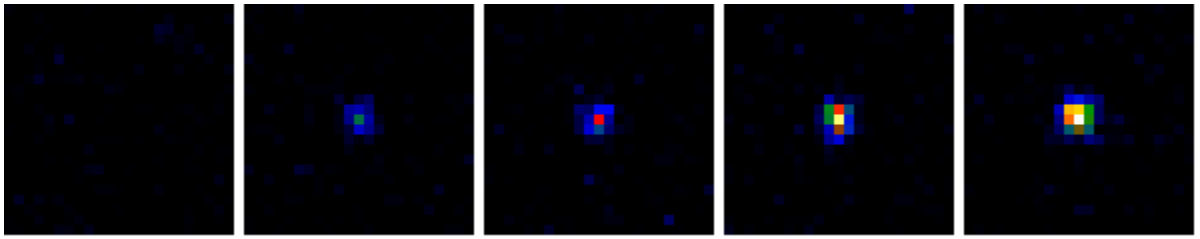
  Recent progress: cavity signals extended from 10 ms to > 100 ms

Start with one atom in lattice

- Single atom magneto-optic trap (MOT)
- Transfer atoms into 1-D lattice optical dipole trap
- Continuous observation of atoms in lattice

  A neutral atom quantum register!

Single Atom MOT

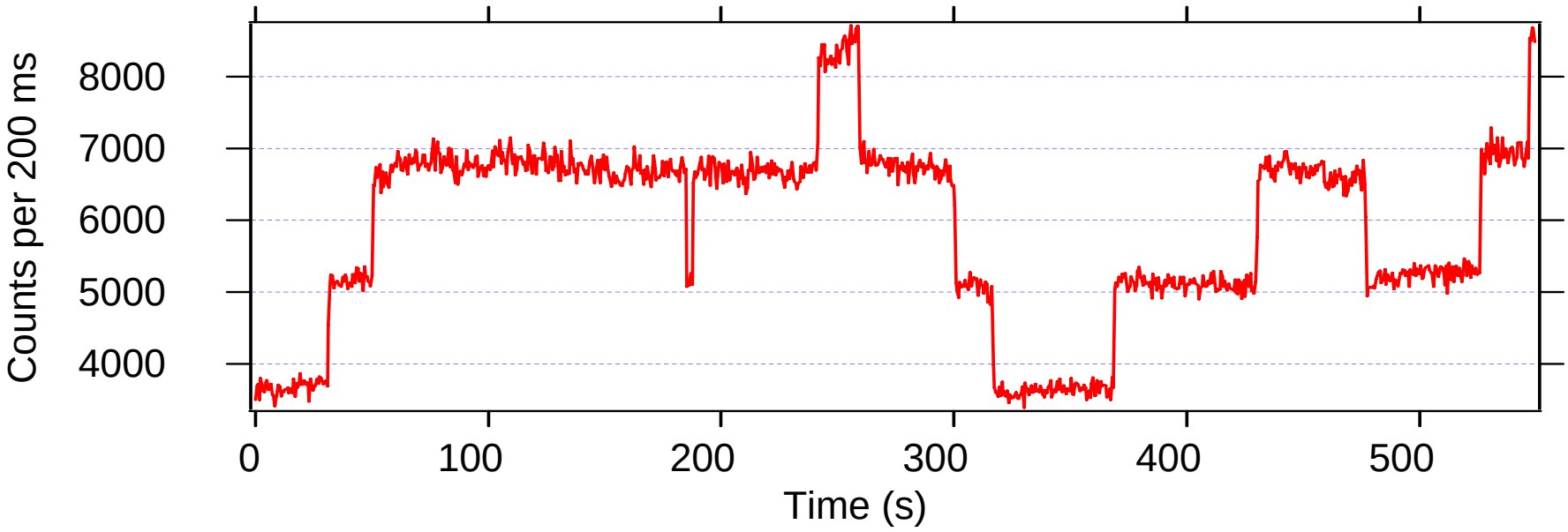


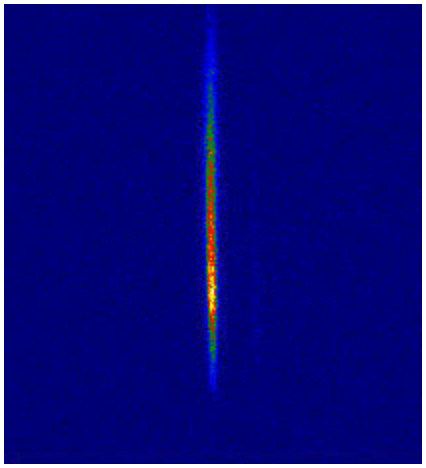
0 1 2 3 4

Loading and counting individual
neutral Rb atoms

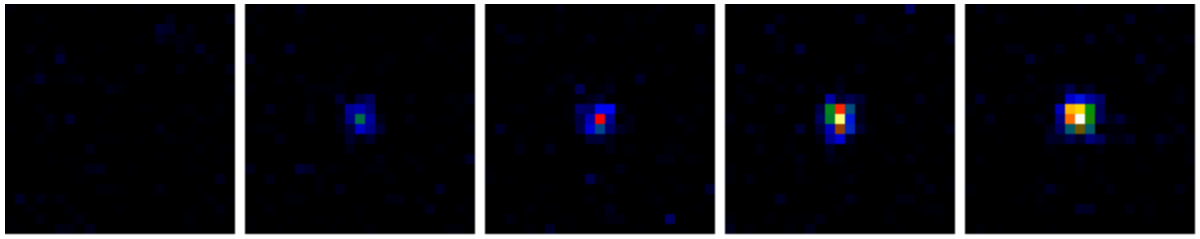
Looking for single trapped atoms

Flourescence in a MOT



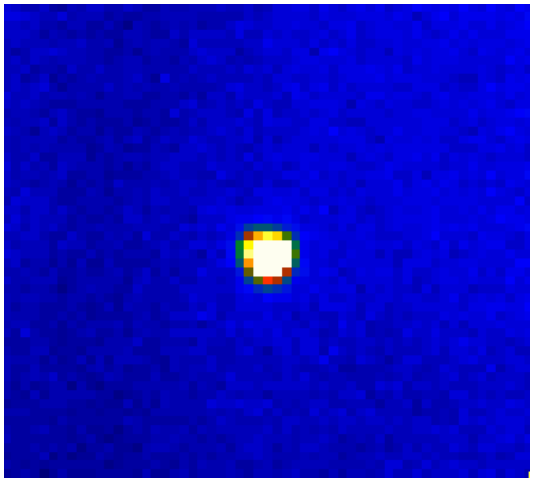


~10,000 atoms in a lattice
P =.9W, 1.2mK frame is ~.25mm long

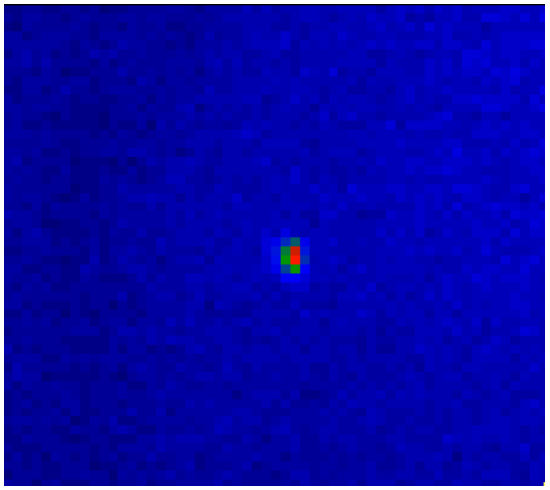


0 1 2 3 4

Imaging Atoms in Optical Lattice



6 atoms in MOT



3 atoms transferred into lattice

FORT

$\lambda = 1064nm$

$w_0 = 17\mu m$

$U = 600\mu K$

IMAGING in FORT

Exp time=1.5s

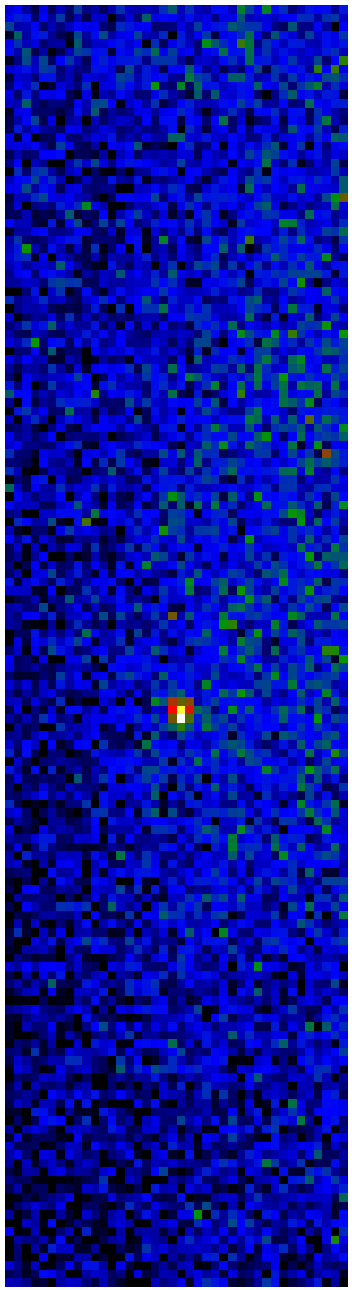
s=.0061 per beam

Count rate=2700/s

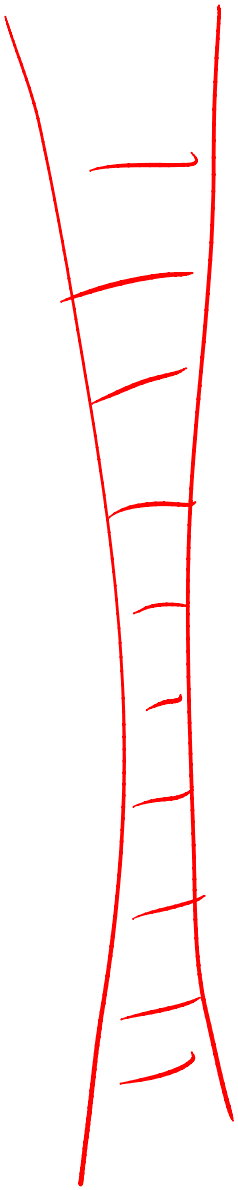
Using a 6 beam MOT with balanced radiation pressure we are able to image the atoms directly in the Optical Lattice

Really new data

0.5 sec / frame

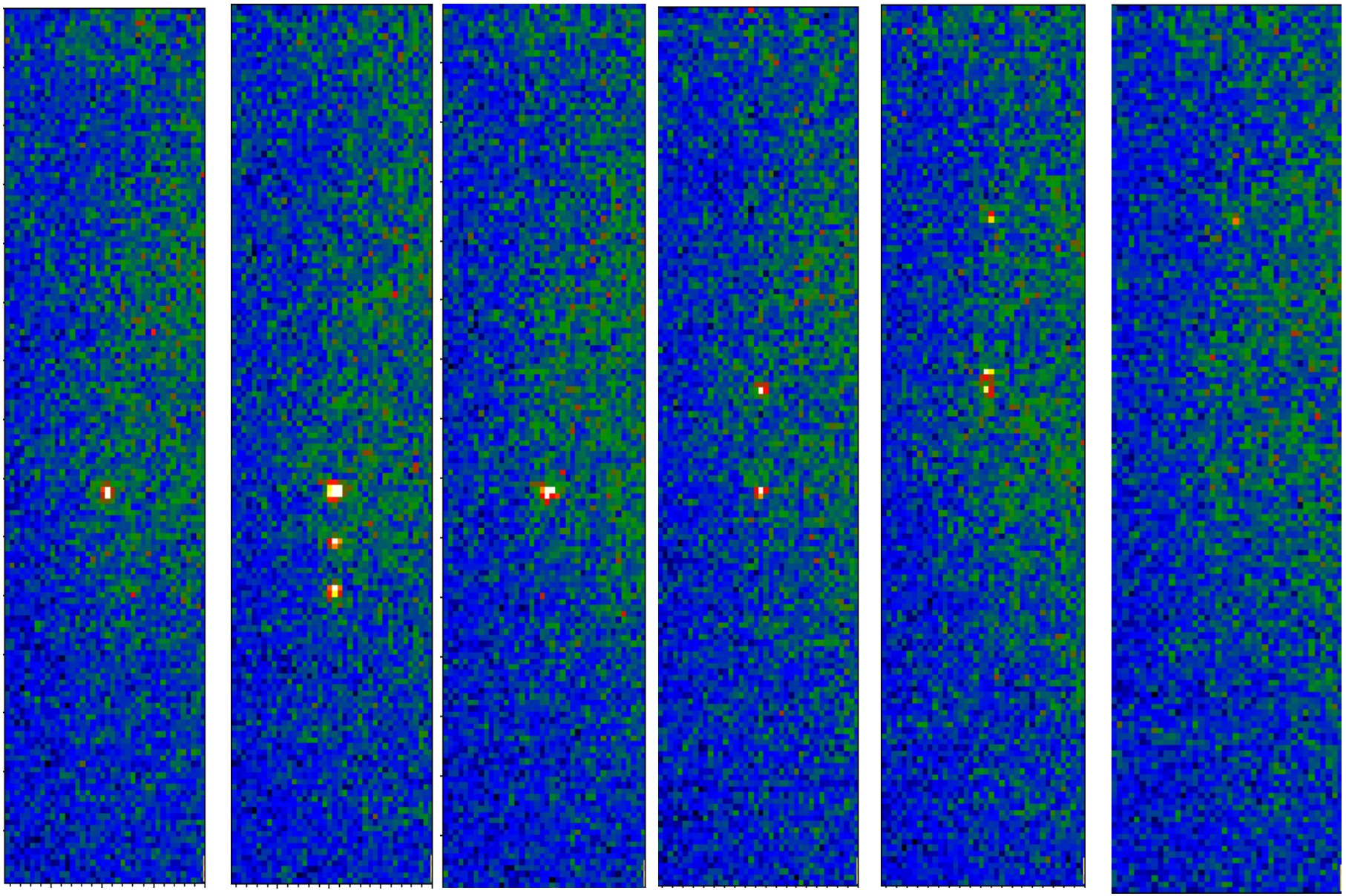


MOT location



YAG lattice

10 am Mountain Time Today



Atoms in MOT

MOT Coils Turned off t=0

Atoms in Dipole trap t=5s

t=10s

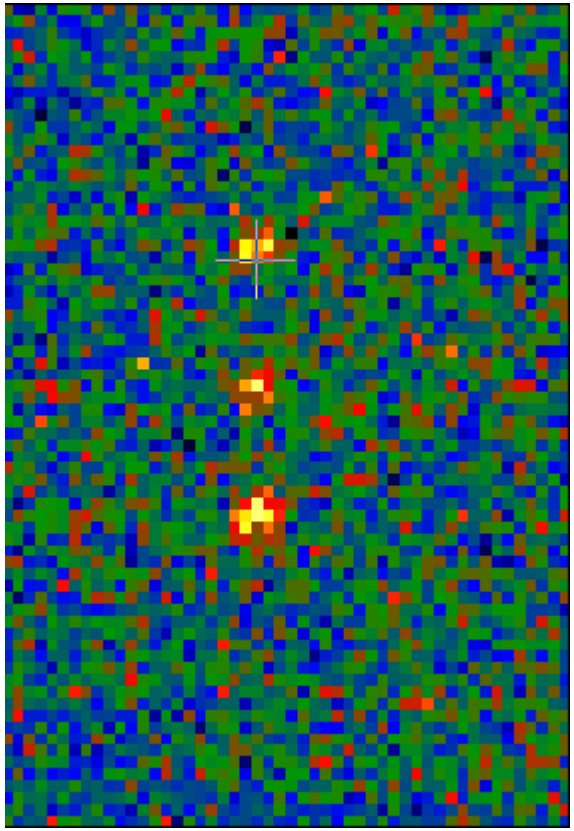
$\Delta x = 170\,\mu\mathrm{m}$

t=55s

$\Delta x = 290\,\mu\mathrm{m}$

t=244s

40 mins ago



3 atoms in a row

$50\mu m$ separation

Don't look back. Something might be gaining on you.
Satchel Paige

ARDA roadmap goals

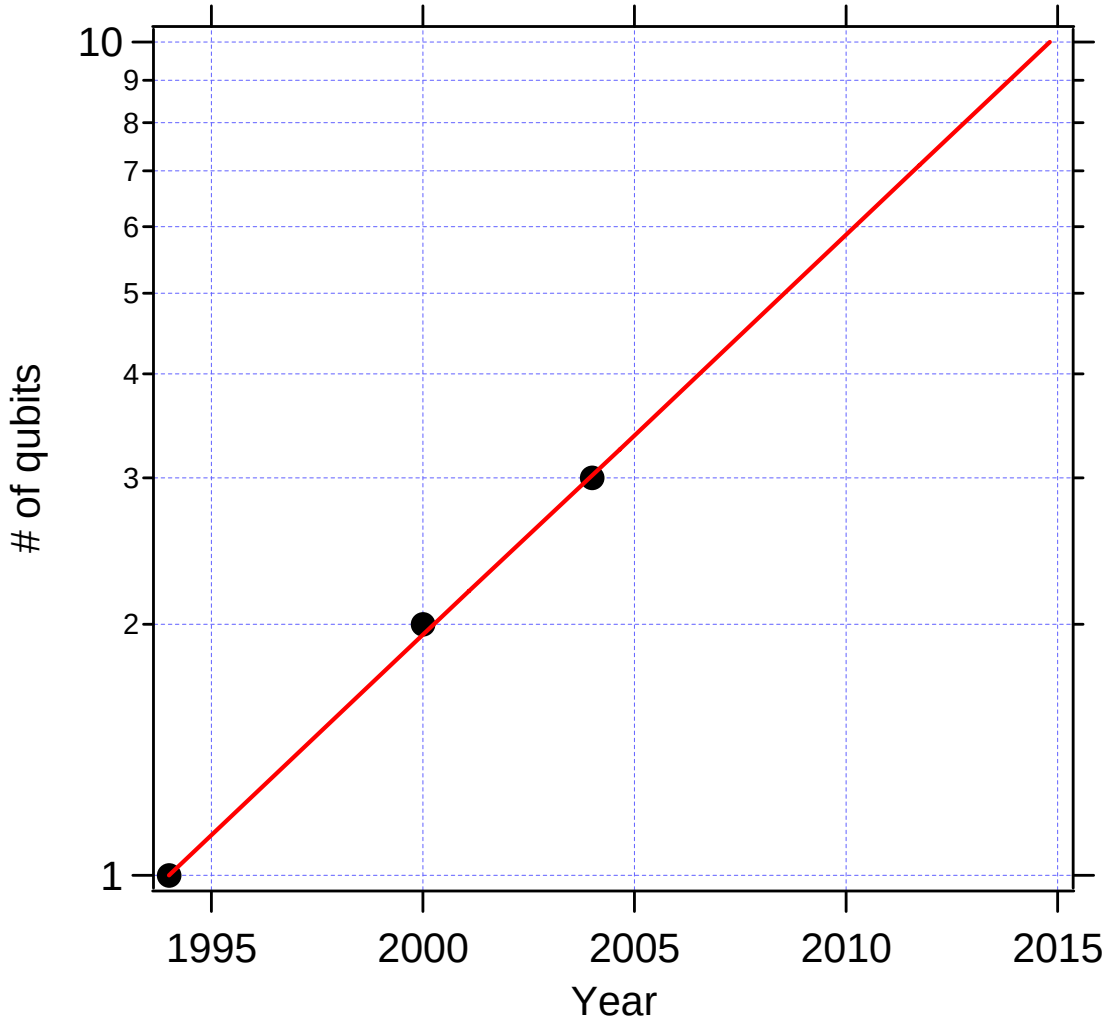
Year 2007 goals (requires ~10 physical qubits)

- encode a single qubit into the state of a logical qubit formed from several physical qubits,
- perform repetitive error correction of the logical qubit
- transfer the state of the logical qubit into the state of another set of physical qubits with high fidelity,

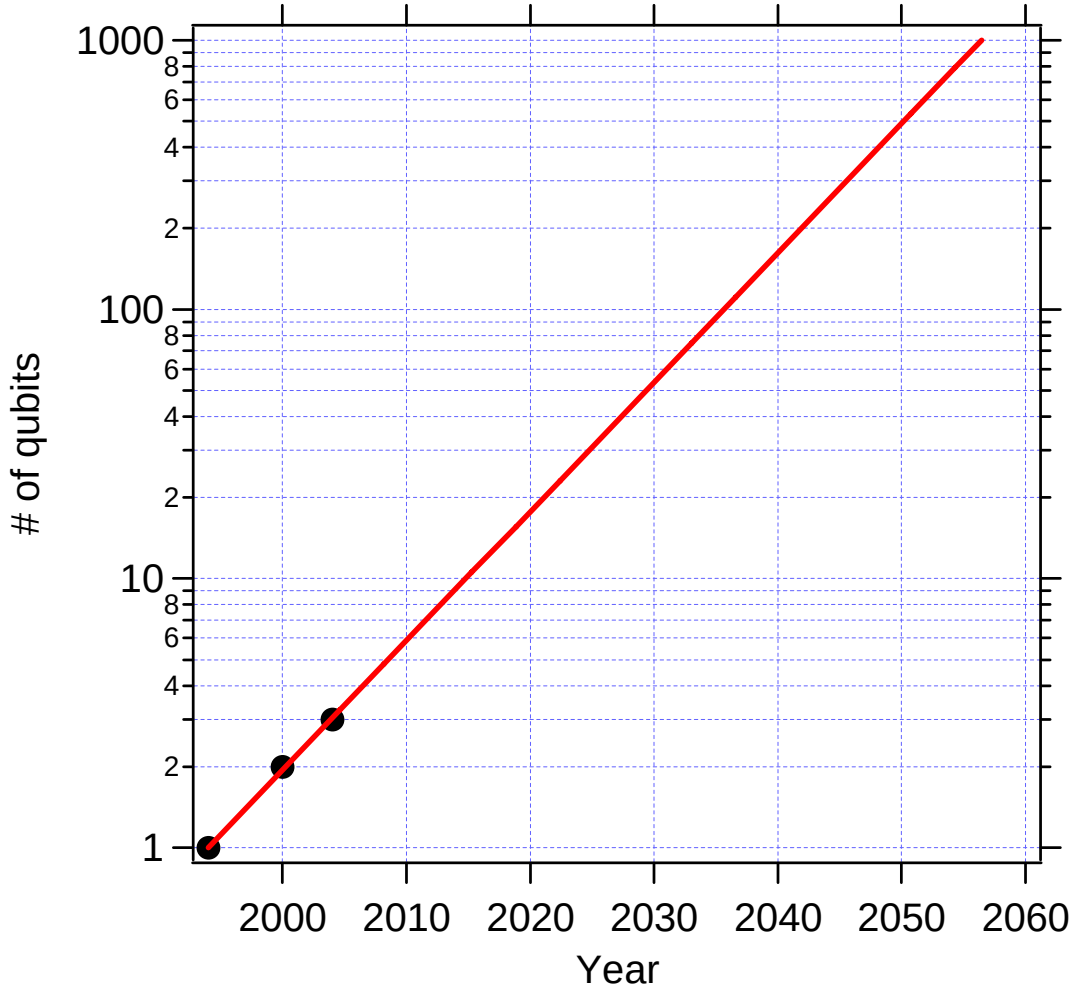
Year 2012 goals (requires ~50 physical qubits)

- implement a concatenated quantum error-correcting code.
- exercise multiple logical qubits through the full range of operations required for fault tolerant QC in order to perform a simple instance of a relevant quantum algorithm

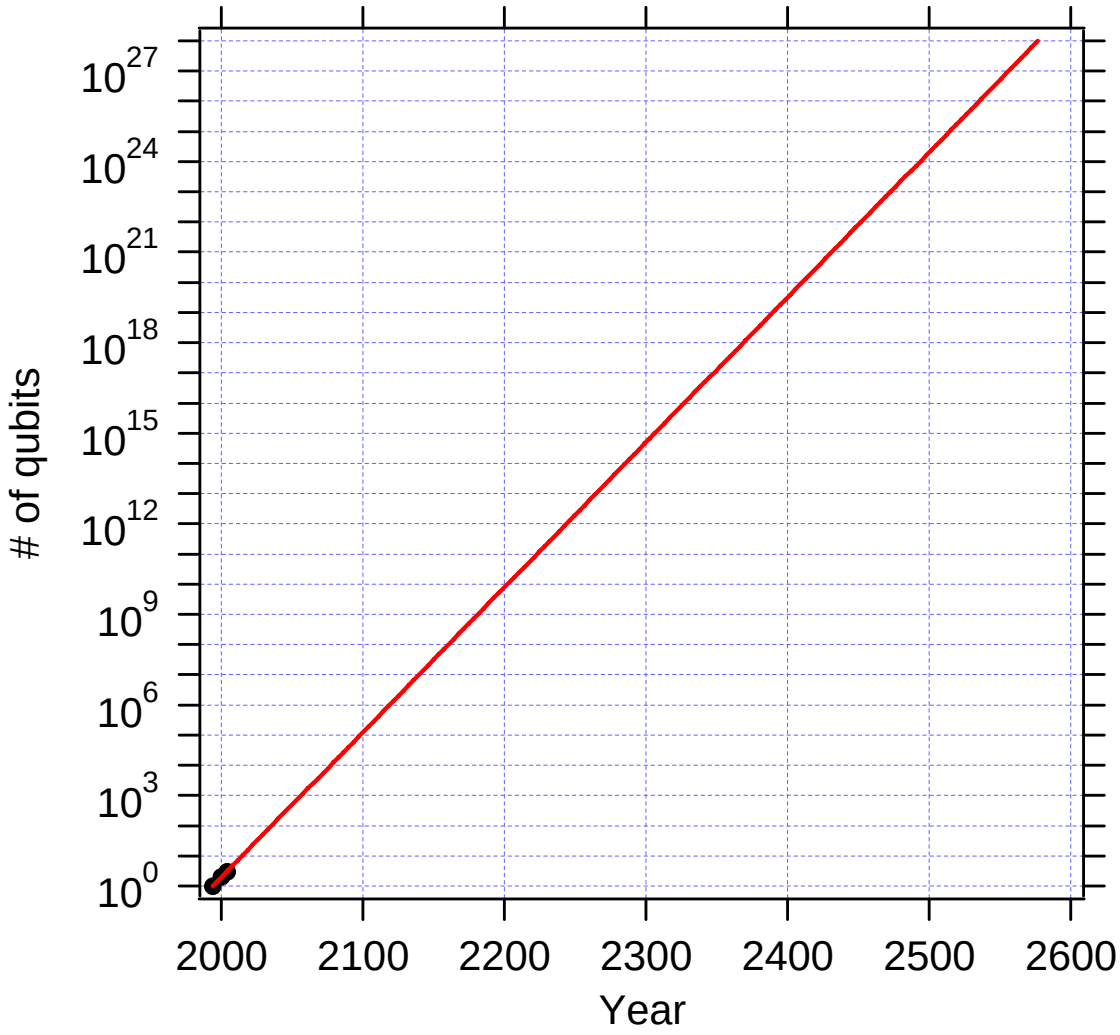
Moore's law for ion traps



Moore's law for ion traps



Moore's law for ion traps



QC Approach	The DiVincenzo Criteria							
	Quantum Computation						QC Networkability	
	#1	#2	#3	#4	#5		#6	#7
NMR								
Trapped Ion								
Neutral Atom								
Cavity QED								
Optical								
Solid State								
Superconducting								
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.							

Legend: = a potentially viable approach has achieved sufficient proof of principle

 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

 = no viable approach is known

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.


Eva Bookjans
Layne Churchill
Adam Steele
Michael Gibbons
Qin Qishu
Kevin Fortier
Nate Brown
Ming Shien Chang
Soo Kim